COAL POWER & COMBUSTION

Office of Fossil Energy

Energy Research and
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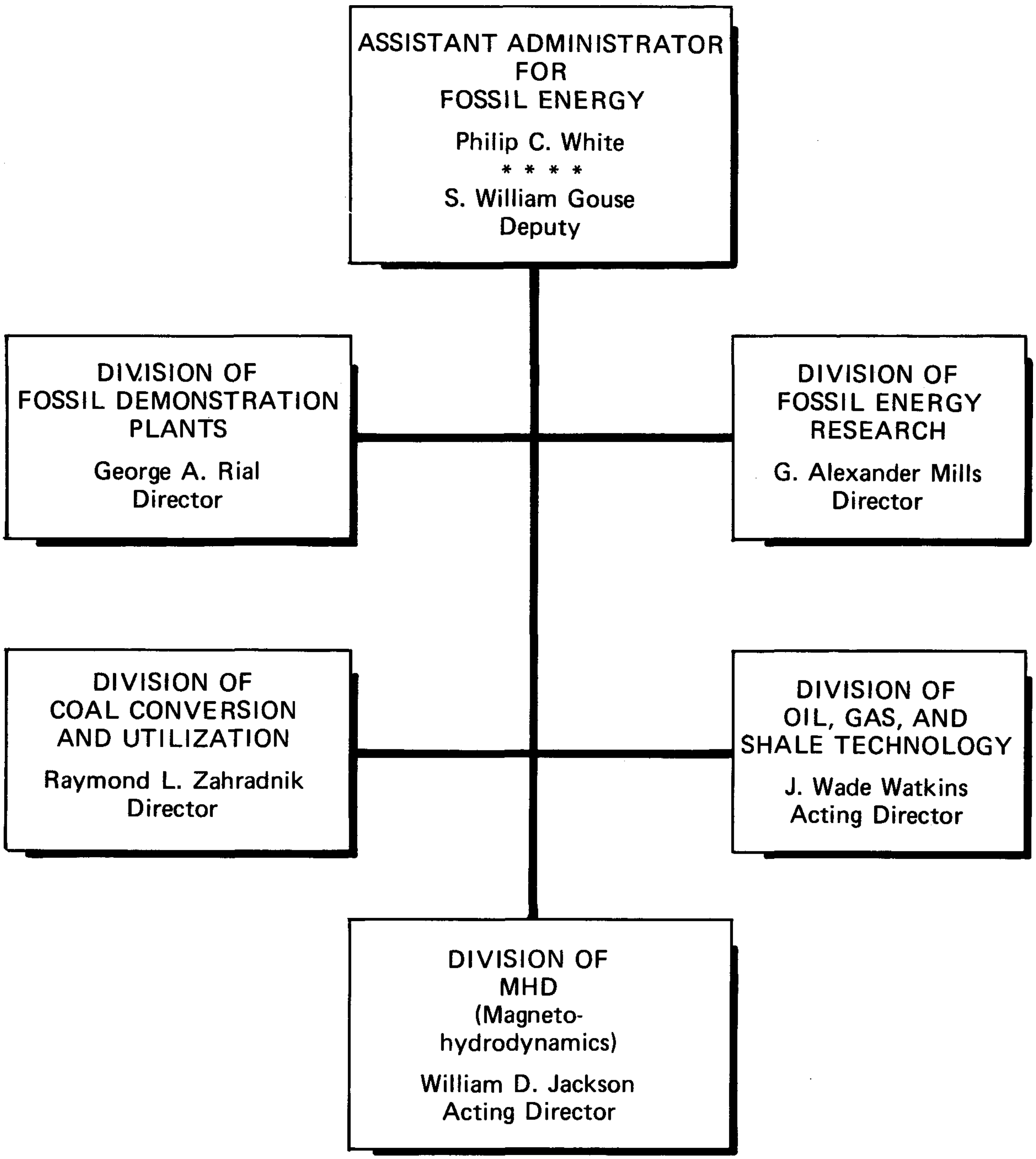
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EXECUTIVE SUMMARY

The United States has more energy available in the form of coal than in the combined resources of petroleum, natural gas, oil shale, and tar sands. Nationwide energy shortages, together with the availability of abundant coal reserves, make the use of coal vital to the nation's total supply of clean energy. In response to this need, the Office of Fossil Energy of the Energy Research and Development Administration (ERDA) is conducting a research and development program to provide the technology for rapid commercialization of processes for improved direct combustion of coal and for converting coal to synthetic fuels. These fuels must be suitable for power generation, transportation, storage, and residential and industrial uses. The technologies selected for development (gasification, liquefaction, and combustion) satisfy an urgent need for a particular type of fuel, are potentially feasible both technically and economically (in terms of research and development costs and the costs of the final product) and will not exceed the air, water, and solid pollution standards established by the Environmental Protection Agency (EPA). The emphasis given to each of the technologies varies depending upon factors such as technical complexity, stage of development (laboratory research, including bench-scale tests and experiments with process development units, and pilot plant design, construction, and operation), flexibility of the use of the fuel produced, and the urgency of the energy need that the technology is designed to satisfy.

ERDA's coal combustion and power program, started by the Office of Coal Research (OCR) of the U.S. Department of the Interior (merged into ERDA in January 1975), has focused on two major areas: direct combustion of coal and advanced power systems. For direct combustion systems, current emphasis has been placed on (1) development of atmospheric and pressurized systems capable of burning high-sulfur coals of all degrees of rank and quality in fluidized-bed combustors, (2) development of the ability to burn coal-oil slurries in substitution for oil-fired combustors, and (3) improvement in the efficiency of present boilers. Contrasted with conventional coal-fired systems, fluidized-bed combustion systems result in higher power generation efficiencies and cleaner exhaust gases, even when burning high-sulfur coals. If the fluidized-bed system is pressurized, additional economies in capital costs (through decreased construction expenses) and in operating costs (through increased efficiencies) may be realized. The benefits from high-pressure combustion are (1) a reduction of furnace size due to decreased gas volume and (2) an increase of sulfur removal ability.

The advanced power systems program is directed toward developing electric power generation systems that operate on coal or coal-derived fuels. These systems will have lower electricity costs than those achievable in new steam power plants of current technology.

To develop direct combustion and advanced power systems as quickly as possible, ERDA is sponsoring research and development projects. Responsibility for designing, constructing, and operating a 30 Mw, atmospheric pressure, fluidized-bed boiler at the Monongahela Power Plant in Rivesville, West Virginia, was contracted to Pope, Evans and Robbins, Inc. This improved combustor design is to be used to produce steam for conventional power generation. The novel features of this system include sulfur removal during combustion and the use of modular "cells" to facilitate construction and increase reliability and maintainability. The Lewis Research Center, National Aeronautics and Space Administration, through contracts with General Electric Company and Westinghouse Electric Corporation, is conducting an energy conversion alternatives study. Both Combustion Power Company, Inc., and Argonne National Laboratory are studying fluidized-bed combustion. The former is developing a hot-gas cleanup system for an open-cycle gas turbine for an electric power generation system utilizing coal rather than oil and combining desulfurization with combustion. The latter is evaluating the engineering and scientific aspects of fluidized-bed combustion and sulfur dioxide absorption at elevated pressures. Oak Ridge National Laboratory is developing an externally fired gas turbine power generation system for use in a modular integrated utility system, with each module having a capacity of 0.5 Mw. Such generating systems can be economically practical only by efficient recovery of heat from the turbine exhaust gases. The Pittsburgh Energy Research Center is running a coal-oil slurry combustion program and a Solvent-Refined Coal (SRC) combustion test program, and Morgantown Energy Research Center is running a program on anthracite refuse utilization. The National Research Development Corporation is researching the combustion science features of pressurized fluidized-bed furnaces. Other projects include studies of high-temperature dust control by the Construction Engineering Research Laboratory; analysis of applications of fluidized-bed combustion technology by Exxon Research and Engineering Company; R&D planning assistance services provided by The MITRE Corporation; and technical and engineering services provided by Gilbert Associates, Inc.

During the fourth quarter of 1975, much of the remaining equipment required for completion of the ***Multicell Fluidized-Bed Boiler*** was received. General construction work completed during the quarter included fabrication of hangers for seven boiler feeders; erection of scales, air preheater rotor and shell, and air blowers; installation of conveyors; and erection of all structural steel. Work to expedite the procurement of equipment continued, the design of the concrete equipment foundations was approved; and contract amendments and change orders, required because conditions in parts of the plant were different than originally indicated, were proposed. Laboratory research included continued analysis of Germany Valley limestone and Greer limestone. Generally, for coals with more than about 2.5 percent sulfur, the Greer limestone was more efficient for sulfur capture; for coals with less than 2.5 percent sulfur, Germany Valley limestone was preferred. Among other activities were study of the chemical process of sulfur capture in limestone, including the effects of salt additives; work on a technique for reducing the data from the chemical analysis of the bed, fly ash, and dust samples; investigation of the effect of salt additive on sulfur capture; initiation of a test program to study the effects of bed depth and gas velocity on heat flux to the tube bundle; and conduct of three tests to determine the effect of bed particle size on the rate of heat transfer from the bed to the tubes submerged in the bed.

The parametric analyses required for the ***Energy Conversion Alternatives Study (ECAS)*** were nearly completed. However, so that completion of the report on this effort would not affect work on conceptual designs, the date for publication of the final report was delayed. The development of conceptual designs continued throughout the quarter. Some delays were experienced, however, because of delays in receiving fuel samples for determining semiclean fuel specifications. The samples were received during this period, but the equipment for filtering the fuel is still being fabricated and assembled.

The moving-bed granular filter was installed in the ***Pressurized Fluidized-Bed Combustor and Turbine Power Generation*** process development unit and, after preliminary testing and adjustments, appeared to be performing well. Low-pressure circulation of the filter medium with the granular filter on-line was accomplished. A test was conducted to evaluate system heatup parameters but was terminated early because the inlet louver screen collapsed. In recent tests, higher corrosion rates have been occurring, possibly because of the use of a different coal with a higher phosphorous content. Analyses of the coal ash from these runs were inconclusive as to the source of the increased corrosion. Analyses of the coal, cyclone ash, dolomite and turbine deposit specimens by Westinghouse are continuing. The turbine deposit analysis indicates that it was composed primarily of agglomerated sulfated dolomite fines. Tests were initiated as part of the baseline characterization needed to assess the influence of contaminants on scale structure in subsequent tests.

Supportive Studies of Pressurized Fluidized-Bed Combustion during the quarter included continuing research on combustion, sulfation and regeneration, and sulfur recovery and emission control. Emphasis in combustion studies was placed on initiation of an experimental program to evaluate the effects of recycling on sorbent performance and decrepitation. Among the sulfation and regeneration studies were further tests of α-alumina pellets impregnated with calcium oxide to determine their sulfur retention capability, their ability to be regenerated, and their integrity during fluidization. Oxides of barium, potassium, sodium, and strontium on α-alumina were also tested as sorbents. One-step regeneration experiments were conducted in the newly modified bench-scale regenerator. The extent of regeneration was improved, primarily because of the larger inside diameter of the regenerator which improved the length-to-diameter ratio of the fluidized bed. This improved ratio in turn improved the quality of fluidization. Analyses of solid-solid reactions continued to be emphasized in sulfur recovery and emission control studies. Among other activities during the quarter were (1) additional experiments to determine the vaporization characteristics of trace elements in coal and their rate of volatilization and (2) experiments to gain a better understanding of the quality of fluidization and to correlate minimum fluidization velocities with the particle size distribution of the solids in the bed, bed temperature, and reactor pressure.

For the ***Externally Fired Gas Turbine for Modular Integrated Utility System (MIUS)***, the contract for the design of the engine was approved. Modifications to the existing turbine-generators to adapt them for use in MIUS and the results of cycling tests were discussed with the contractor. The furnace design was revised during this period to reduce the number of flange joints and their sensitivity to warpage. Performance of the ceramic gasket material in tests was favorable; additional tests will be conducted to determine the effect of clamp pressures on air leakage rates. Laboratory research activities included installation of the coal feed and metering systems. Difficulties with the motor necessitated the purchase of a larger motor, which is now performing satisfactorily. The 4-foot-square cold-flow reactor performed as expected. This equipment was then modified, and a second test was initiated.

Work on the ***Coal-Oil Slurry Combustion Program*** focused on the completion of a preliminary shakedown test in a 100 hp firetube boiler using No. 6 fuel oil. Boiler efficiency was tentatively determined to be about 85 percent. Preparations for a 1,000-hour slurry test were nearly completed, and the first batch of slurry was mixed. The test will be started in January. In addition, about 90 percent of the facility bid package specification for the 700 hp watertube boiler was completed. Plant layout drawings were prepared for the coal-oil slurry preparation equipment, the combustion test facility, and the flue gas cleanup system, and detailed drawings were prepared for seven major vessels.

For the ***Solvent-Refined Coal (SRC) Combustion Test Program***, new burners were designed and fabricated to minimize the contact of SRC with hot metal surfaces. (Early SRC combustion tests resulted in sticking and eventual clogging of burner passages because the SRC was too hot.) In combustion tests with the modified burners, satisfactory combustion results were achieved without appreciable deposit formation or burner fouling. To optimize recirculation and flame shape and to overcome burner fouling, swirl in the secondary air stream was reduced and a longer flame established. Although flame temperatures obtained with SRC were several hundred degrees higher than those obtained with bituminous coal, the emission of nitrogen oxides was considerably lower than that obtained with coal fired through the more conventional burners originally used in the combustion system. Carbon conversions exceeded 99 percent, which is similar to the conversion obtained when bituminous coal is burned.

As part of the study of ***Anthracite Refuse Utilization,*** two test runs were made in a fluidized-bed combustor. An anthracite culm material from the Mid-Valley Bank in northeastern Pennsylvania was burned. In the first run, the bed was built solely with culm material, and, so that the amount of sulfur dioxide released could be determined, no limestone was used. In the second run, moderate amounts of limestone were added to limit sulfur dioxide emissions. It was determined that lower amounts of limestone than used in the run could be used to regulate the emission of sulfur dioxide according to EPA standards.

A contract modification for ***Pressurized Fluidized-Bed Combustion Research*** was approved during the quarter to include three additional fluidized-bed tests. Alteration of the equipment to accommodate these tests was begun.

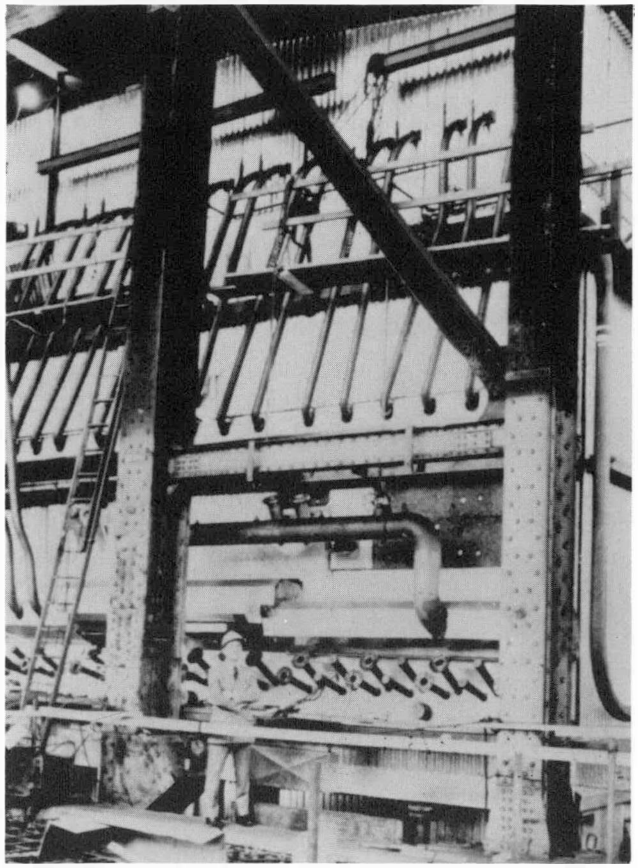
Work on ***High-Temperature Dust Control*** included modification of the design of the test apparatus for measuring the velocity and dust load of the flue gas stream to include a venturi velocity meter and a manual stack sampler instead of automatic continuous monitors. Procurement of equipment is under way. However, because of problems in obtaining replies from subcontractors to requests for quotations on fabrication of the ductwork and the test sections, the fabrication and installation task is approximately 2 months behind schedule.

Studies of ***Applications of Fluidized-Bed Combustion Technology to Industrial Boilers*** involved the development of technical requirements for representative industrial fluidized-bed boilers. Previous cost estimates were extended to include boilers with larger and smaller capacities than 100,000 pounds per hour. Also, coal consumption statistics were reviewed, a marketing strategy for the introduction of fluidized-bed combustion technology to potential industrial users was suggested, and some advantages of coal-fired fluidized-bed combustion technology were outlined. In addition, the market survey of selected industries was planned to learn the attitudes of the industries toward coal firing and fluidized-bed technology.

R&D Planning Assistance Services provided to ERDA during the fourth quarter of 1975 included work on projects related to both advanced power systems and direct combustion systems. Activities pertaining to advanced power systems included assistance with the preparation of a national program plan, review of "A National Plan for Energy RD&D: Creating Energy Choices for the Future," survey of open-cycle gas turbine development, and evaluation of ceramic component technology. Among the activities supporting direct combustion systems projects were the updating of Volume II of the national fluidized-bed combustion program plan, assistance to the Morgantown Energy Research Center in developing design criteria for a Component Test and Integration Facility, and provision of technical and engineering inputs related to the multicell fluidized-bed boiler being developed by Pope, Evans and Robbins, Inc.

Technical and Engineering Services in support of ERDA's combustion program included continuing design review and construction management assistance with the multicell fluidized-bed boiler project being developed by Pope, Evans and Robbins and preparation of a draft report on an engineering economy study of the modular integrated utility system. Gilbert also assisted ERDA in work on the proposed Component Test and Integration Facility for studying atmospheric fluidized-bed combustion systems. Work on cleanup systems for use with fluidized-bed combustion systems included studies of methods of sampling and measuring particulates in combustion systems, support of ERDA's effort to evaluate and select stable and regenerable sorbents for sulfur removal, and review of developments in high-temperature, high-pressure particulate removal systems.

I. MULTICELL FLUIDIZED-BED BOILER



POPE, EVANS AND ROBBINS, INC.
NEW YORK, NEW YORK

Contract No. E(49-18)-1237
Total Funding: $14,300,000

INTRODUCTION

A multicell fluidized-bed boiler is being developed by Pope, Evans and Robbins, Inc. (PER), under the sponsorship of ERDA. The objective of this program is to design, construct, and operate a prototype multicell fluidized-bed boiler at an electric utility power station as a method of burning high-sulfur or corrosive coals in an environmentally acceptable manner and without excessive maintenance problems. The system is to have a capacity of 30 Mw and is to be operated under typical electric utility conditions. In addition to developing the boiler, PER is conducting a laboratory research program to optimize certain boiler and operational features. Experience gained from designing and operating the boiler and from laboratory research will be used as the basis for scaling up to a 200 Mw multicell fluidized-bed boiler system. The schedule for development of the fluidized-bed boiler is provided in Figure I-1.

PROCESS DESCRIPTION

The fluidized-bed boiler is 12 feet wide, 25 feet high, and 38 feet long; has conventional water tube walls and a convection economizer; and has a capacity of 300,000 pounds of steam per hour. However, the boiler is unique in that it has horizontal tube bundles submerged in the bed of fluidized coal, ash, and limestone, which is the combustor. The unit is divided into separate cells, three of which are almost equal in size. The fourth cell, the carbon burnup cell, is smaller in width due to its own design requirements. The dimensions of the cells were influenced by shipping limitations, duty requirements, and the anticipated function of each cell. The design of the cells was based on the intended heating function:

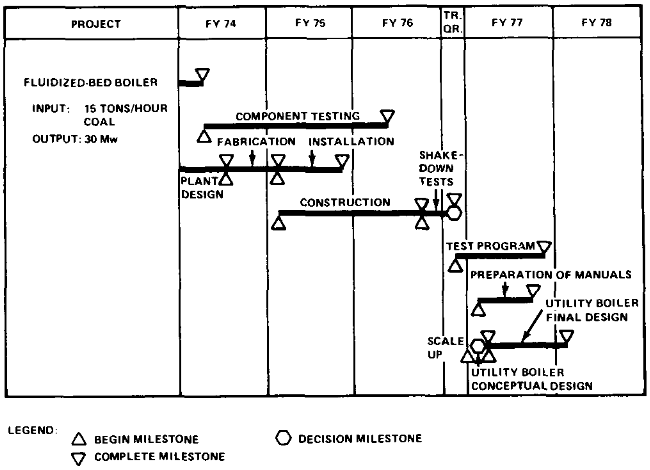


Figure I-1. MULTICELL FLUIDIZED-BED BOILER PROGRAM SCHEDULE

Cell A, the primary superheater, has a horizontal superheater tube bundle submerged in the bed, with two additional horizontal bundles, the evaporator, and economizer located in the convection zone (free board).

Cell B, the finishing superheater, has a horizontal bank of finishing superheater tube bundles in the bed zone with horizontal boiler and economizer surfaces in the convection zone.

Cell C, has a horizontal boiler tube bundle in the bed zone and boiler and economizer surfaces in the convection zone.
Cell D, the carbon burnup cell, contains only horizontal economizer tubes in the convection zone.

The fluidized bed is located approximately where the grate would be in a conventional coal-fired boiler. The bed thickness would be 4 feet with a 6-foot free zone above it and a 6-foot deep, convection heat transfer volume above that. The partition walls between the cells are the membrane type, i.e., finned tubes without refractory protection.

Coal and limestone are fed to cells A, B, and C, and are fired with air containing oxygen 3 percent in excess of the stoichiometric quantity. Approximately 0.1 pounds of carbon per pound of coal feed are elutriated from these cells and collected in a mechanical dust collector. This material is then sent to Cell D and burned with 25 percent excess air. The coal is burned in an inert ash or sulfur-absorbing limestone fluidized bed at nominal bed temperatures of 2,000° F in the carbon burnup cell and 1,550° F in cells A, B, and C. The mixing tendencies of the fluidized bed are controlled by using boiler tubes as baffles and walls. Movement of the particles from one portion of a cell to another is caused by the inherent fluid-like behavior of a fluidized bed.

One of the advantages of the multicell fluidized-bed boiler is that sulfur dioxide and nitrogen oxide emissions are well within EPA standards; expensive and energy-consuming flue gas cleaning equipment is not required. The sulfur dioxide is controlled by the use of limestone, which acts as an absorber. The limestone will be kept reactive by regeneration to recover concentrated sulfur dioxide and by the addition of fresh limestone. Emissions of ash particles, which are removed from the flue gas using conventional gas cleanup equipment, are also low because the coal is not pulverized, resulting in a mean dust-particle size of 100 microns compared to 20 microns for conventional coal preparation equipment.

There are several other advantages to the fluidized-bed boiler:

- Low-quality, high-sulfur coal can be burned without danger of slagging because of low combustion temperatures.
- The heat release and heat transfer coefficients are high, which reduce boiler size, weight, and cost. Cost analyses indicate that the 200-Mw-size fluidized-bed boiler will weigh 2,760 tons, compared to 6,000 tons for a conventional 200-Mw-size boiler, and will cost $5.9 million less.
- The multicell design lends itself to mass production assembly of the major components, facilitating shipping and saving plant building time.
- It is anticipated that use of the fluidized-bed boiler, rather than a conventional coal-fired boiler requiring a flue gas cleanup system, will result in an overall cost savings for the boiler of up to 35 percent.
- The overall operating efficiency of the multicell fluidized-bed boiler power plant is projected to be 39 percent, compared to approximately 37 percent for a conventional coal-fired plant with stack-gas cleanup operating with the same coal and at the same steam pressure and temperature.

HISTORY OF THE PROJECT

In February 1965, OCR (now part of ERDA) awarded PER a contract to build and operate a small atmospheric fluidized-bed boiler. The ability to meet the most rigorous air pollution standards while burning high-sulfur coals was demonstrated, and ash fouling and slagging problems common to other types of boilers were eliminated. Furthermore, the boiler promised improved power plant efficiency and cleanliness when burning chars, anthracite, or conventional coal and eliminated the need for pulverization of the coal feed.

Under another OCR contract, initiated in May 1972, PER (in its Alexandria, Virginia, laboratory) performed additional experimental work using a small-scale (0.5 Mw) unit. Four types of fuels (two high-sulfur bituminous coals, North Dakota lignite, and a petroleum coke) were burned to demonstrate the feasibility of fluidized-bed combustion and to examine the effect of lignite's high sodium content. The results of this work indicated that the addition of small quantities of common salt to the fluidized bed was a useful method for increasing limestone utilization, that chloride emissions were low, and that corrosion due to the addition of salt did not occur. Sulfur oxide emissions were reduced to levels well below the emission standards of existing and proposed federal and local regulations.

Because the previous work indicated a high probability of success, work under the current contract was initiated, in October 1972, to design, construct, and operate a 30-Mw-size multicell fluidized-bed boiler under practical utility conditions. For proper design development sizing of the 30 Mw boiler, a concept for an 800-Mw-size fluidized-bed boiler was developed, consisting of four modules, each containing seven vertically stacked fluidized-bed cells. The modular construction results in a four-to-one turndown ratio plus a two-to-one turndown ratio for each module, resulting in an overall plant turndown capability of eight to one. Steam pressure and temperature conditions of the boiler were designed to meet the requirements of the site at which the boiler was installed–the power plant of the Monongahela Power Company at Rivesville, West Virginia. Responsibility for constructing the 30 Mw boiler was awarded to Foster Wheeler Energy Corporation. Foster Wheeler is also responsible for (1) preparation of the designs, technical specifications, arrangement drawings, bills of materials, etc., for the boiler and the pumps, valves, and burners directly attached to the boiler; (2) preparation of a fluidized-bed boiler test program; and (3) design, construction, and testing of a cold model. Champion Construction and Engineering Company, Inc., was awarded responsibility for general construction work at the plant site and for scheduling shipments of structural steel, motors, pumps, etc. Champion and PER jointly review and approve structural drawings prior to fabrication.

Shop fabrication of the 30 Mw boiler was completed in 1974, and the field erection of the boiler in the Monongahela Power Company power plant was started. Auxiliary systems and plant general construction (including boiler and plant controls) and laboratory construction were also started in 1974. Operations will start in 1976.

Concurrent with work on the 30 Mw boiler, PER has continued its laboratory research program, including cold-model and fluidized-bed module tests.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

During the fourth quarter of 1975, much of the remaining equipment required for completion of the multicell fluidized-bed boiler was received. General construction work completed during the quarter included fabrication of hangers for seven boiler feeders; erection of scales, air preheater rotor and shell, and air blowers; installation of conveyors; and erection of all structural steel. In addition, work to expedite the procurement of equipment continued, the design of the concrete equipment foundations was approved; and contract amendments and change orders, required because conditions in parts of the plant were different than originally indicated, were proposed. Laboratory research included continued analysis of Germany Valley limestone and Greer limestone. Generally, for coals with more than about 2.5 percent sulfur, the Greer limestone was more efficient for sulfur capture; for coals with less than 2.5 percent sulfur, Germany Valley limestone was preferred. Among other activities were study of the chemical process of sulfur capture in limestone, including the effects of salt additives; work on a technique for reducing the data from the chemical analysis of the bed, fly ash, and dust samples; investigation of the effect of salt additive on sulfur capture; initiation of a test program to study the effects of bed depth and gas velocity on heat flux to the tube bundle; and conduct of three tests to determine the effect of bed particle size on the rate of heat transfer from the bed to the tubes submerged in the bed.

Boiler Design and Construction

During the quarter, much of the accessory equipment required for the multicell fluidized-bed boiler was received. With receipt of this equipment, Foster Wheeler will be able to complete the erection of the steam generator. The work will be rescheduled so that it will coincide with the completion of the work by the general subcontractor, Champion Construction. By the end of this period, about 99.5 percent of the scheduled Foster Wheeler design and testing work had been completed. Erection work on the steam generator was 96 percent complete at the end of the quarter. The work still to be finished by Foster Wheeler includes the installation of the boiler recirculating pumps, the large Rockwell check valves, the pneumatic actuators for the slide gate dampers, the fluidization grid plates, horizontal seal plates and insulation and lagging between the plenum chamber and the lower rear wall waterwall headers, and the balance of the miscellaneous vent and drain piping.

General construction work by Champion Construction continued throughout the quarter. Among the tasks completed were the installation and leveling of the coal dryer and crusher and erection of the coal and limestone bins, seven coal feeders, and a 100-foot steel smokestack. Four vibrating conveyors running from the bins to the weight scales, an electrostatic precipitator (except some high-voltage wiring), the forced-draft and induced-draft fans, the air preheater, and four air blowers were installed. At the end of the quarter, the ash cooler was being assembled, and the flue gas duct system, the air supply duct from the forced-draft fan to the boiler, and dust collectors were being erected.

Champion spent a considerable amount of time negotiating and organizing packages for amendments to the contract. These packages were for piping changes, the coal handling system, the fly ash bypass to the silo, and extended supervision and administration. Also during this period, Champion decided to erect the fly ash and bed material piping and associated equipment and to install all of the instrumentation rather than subcontract this work. As of the end of this period, 60 change orders had been approved and issued to Champion. Most of these change orders were required because conditions in some parts of the Rivesville, West Virginia, power plant, constructed about 60 years ago, were different from those originally indicated on the drawings.

To ensure timely deliveries, Champion has continuously worked to expedite the purchasing, fabrication, and shipping of equipment. Material procurement is slow, but has been continuous. One problem area is that Buffalo Forge, the manufacturer of the auxiliary forced draft fan, is on strike. Champion and PER have been advised that no immediate end to this strike is in sight. As a backup, Champion has contacted four other fan manufacturers.

A coordination meeting was held on site with Allen-Sherman-Hoff to discuss problems concerning the bed material conveyor and classifier. Coordination with the electricians was attempted, as well as gathering data to develop a system to safeguard the equipment from thermal destruction while incorporating a way to protect personnel.

Champion completed the design and received approval on all of the concrete equipment foundations. Ragnar Benson has nearly completed all of its major contractual obligations concerning demolition and concrete work.

Champion was instructed by PER to install the coal handling system as in the original drawings. A detail drawing has been developed by Champion which offers a means of accomplishing the coal transfer in the area in question.

Preparation of the operating and maintenance manual for the Rivesville multicell fluidized-bed steam generator and associated equipment supplied by Foster Wheeler was completed during this reporting period. Final copies will be issued during the next period. The calculation procedure section of the test and instrumentation plan was also completed during this quarter.

Laboratory Research

Throughout the quarter, PER continued tests to compare two different limestones and determine the feed rates required for sufficient sulfur capture to meet EPA emission standards during combustion of high-sulfur coal without salt addition. Three tests were run during the quarter: Test 636 using Germany Valley limestone (98.6 percent calcium carbonate) and Tests 637 and 639 using Greer limestone (75 percent calcium carbonate, 4 percent magnesium carbonate, 3.3 percent alumina, and 9.5 percent silica). In all cases, Sewickley coal containing 4.1 to 4.5 percent sulfur was used. The test procedure involved adjusting the calcium-to-sulfur ratio until the sulfur dioxide emission in the stack gas was close to the EPA limit of 1.2 pounds of sulfur dioxide per million Btu of heat released; all operating variables were held constant. The results indicated that, to meet the EPA standard, a calcium-to-sulfur ratio of 3.2 is required for Greer limestone, and a ratio of 4.4 for the Germany Valley limestone. The gas residence time at the Rivesville plant is expected to be 20 percent higher than in the test conditions, so that increased sulfur retention should result.

Because Tests 636 and 637 were of such short duration (1.5 hours) that heat and material balances could not be obtained, Test 639 was made to verify Test 637. It lasted 5 hours in steady-state operation, data being continuously gathered and samples periodically collected. The calcium-to-sulfur ratio was 3.5, resulting in a sulfur dioxide emission rate of 1.1 pounds per million Btu, substantiating the previous results.

A comparison of the two limestones, on the basis of the tests, indicates that for coals containing more than 2.5 percent sulfur, Greer limestone, because of its more favorable internal structure and overall kinetics, appears to be more efficient. For coals containing less than 2.5 percent sulfur, Germany Valley limestone, with its higher calcium content, seems to be more efficient.

To better understand the relative importance of each step in the sulfur capture process the shrinking core model of gas-solid reactions is being used to approximate the chemistry of the system behavior. The chemical process of sulfur capture in limestone has three major steps: diffusion of the sulfur dioxide from the bulk gas phase to the surface of the sorbent particles, diffusion into the sorbent particles, and chemical reaction with both sorbent and oxygen. It is expected that, by fitting kinetic data from sulfur dioxide sorption studies to a mathematical model, information can be obtained to help determine which step in the chemical process limits the sulfur sorption process. The model can also be used for the prediction of optimum process parameters, the variation in process parameters with various limestones and the effect of additives on sulfur capture performance, and for the selection of the most useful limestone.

Several facts can be observed from the calculated results using this model. The expected diffusivity value is about 0.1 cm^2 per second. Increasing the diffusivity above this value has no effect, but decreasing it to 0.01 cm^2 per second has a significant effect particularly where the reaction rate constant is very high. The high dependence of sulfur capture on the reaction rate constant indicates that a rather small increase in catalytic activity could cause a dramatic change in the percent sulfur capture. This could also be achieved theoretically by a rather modest increase in temperature.

PER is developing a technique for reducing the data from the chemical analysis of the bed, fly ash, and dust samples. This method involves simultaneous component balances and uses matrix algebra to calculate the composition of a sample in terms of its macroscopic components from the results of laboratory chemical analysis of test samples. This technique is being computerized and applied to the samples obtained in previous tests.

Two tests were run to determine the effect of adding a sodium compound to the limestone fed into the fluidized-bed combustion chamber on the amount of sulfur dioxide in the flue gas. Test 623 was made using sodium chloride and Test 636 using sodium carbonate. The macroscopic component balance technique described above was used to analyze the "bed" samples, which are separated using 12-, 16-, and 20-mesh screens; "fly ash" samples obtained from the fly ash collector; and "dust" samples collected by an isokinetic sample probe from the stack. All calculations were made on a water-free basis. Five significant results were noted:

- The uncalcined limestone fraction of the bed (from all samples) decreased significantly, the decrease being greatest in the larger particle sizes.
- The coal-derived ash content increased in all fractions of the bed, the largest increases occurring in the particles with the greatest surface area per unit mass.
- A significant decrease was found in the fly

ash collection rate, which increased when salt feeding stopped.

- The coal elutriation rate was decreased by a factor of two, with the limestone that was carried over being more completely sulfated.
- The mean bed-particle size increased 10 percent within 45 minutes after salt feeding was started.

The primary mechanism proposed to explain these results is that small amounts of sodium cause dislocations in the internal structure of the limestone, opening up more pores, thus enhancing the gas diffusion rates and rates of calcination and sulfation. A contributing mechanism may be that molten sodium compounds or eutectics form a sticky layer on the surface of the limestone particle, causing adherence of fine particles and resulting in an increase in the residence time of the fine particles. This would cause the fine coal particles to burn more completely to ash and the fine limestone particles to be more completely sulfated. Also, because of the increase in particle size, fewer fine particles would be carried over into the stack gas.

The conclusion from this study is that the use of a salt additive can result in significant economy of limestone usage, particularly when using high-sulfur coal where the percentage removal of sulfur dioxide must be high. For coals of less than 2.5 percent sulfur, the benefit obtained from using salt depends on the particular limestone used. Another minor point is the effect of salt on coal. A previous study showed that sodium carbonate could be used effectively to enhance coal gasification since it seems to inhibit the rate of "graphitization" of the surface of carbon. Sodium, then, may enhance the combustion of coal by preventing the formation of a less permeable surface layer. Thus, salt may be an oxidation catalyst as well as a sulfur-capture catalyst.

During this quarter, a horizontal tube bundle test program was started to study the effects on heat flux to the bundle of bed depth and of gas velocity at constant preheat and varying preheat. Throughout the test to determine the effect of bed depth, the bed temperature, particle size, and gas velocity were maintained as constant as possible in order to isolate the effect of changing bed mass on heat flux to the tubes. Materials samples were taken during two periods when bed depth was constant. Results showed that the average bed temperature gradually decreased from 1,520° F to 1,350° F as the bed depth increased. The superficial gas velocity throughout the test was between 13 and 10.5 feet per second, the mean particle size remained fairly constant, and a negligible size segregation with respect to height when operating with a 2-foot bed depth was observed. The bed depth increased with time, and the overall bundle heat transfer coefficient varied from 30.5 to 36.5 Btu per hour-foot^2-° F throughout the test with no orderly change with bed depth.

A series of tests was conducted to obtain the overall heat transfer coefficient between the fluidized bed and the water inside the tube bundle. Separate tests were run to determine the effect on the coefficient of superficial gas velocity, particle size, and static height in the bed.

The first test series was to determine the effect of superficial gas velocity while maintaining a constant water flow rate through the tubes, amount of bed material, and bed temperature (at 1,500° F). The oxygen content of the flue gas ranged from 2 to 3 percent. Starting with a coal feed rate of 740 pounds per hour, the goal was to slowly reduce the rate by 100 pounds per hour to allow the system to reach stable conditions. This test had to be terminated because of low bed temperature (1,300° F) when the coal rate was reduced to 660 pounds per hour. A second test series was started in which a duct burner was used to increase air preheat temperature above 600° F. Also, to maintain a 24-inch static bed height, bed material was removed from the furnace through a drain. The starting coal feed rate was 820 pounds per hour. The results showed that the overall heat transfer for the tube bundle was reduced as the superficial gas velocity decreased from 13.5 to 6.9 feet per second, but remained fairly constant when the superficial gas velocity ranged between 13.5 and 14.7 feet per second. The overall heat transfer coefficient was corrected to include the effect of radiative heat. A correction in heat transfer coefficients for radiation to a common temperature of 1,500° F was made. At 1,300° F, the correction changed the overall heat transfer coefficient from 25.8 to 18.5 Btu per hour-foot^2-° F.

Three tests were conducted to determine the effect of bed particle size on the rate of heat transfer from the bed to the tubes submerged in the bed. The mean particle sizes were significantly different for the three tests, but all other parameters that influence heat transfer, such as superficial velocity, bed temperature, and flow of water through the bundles, were held constant. As the tests were run with progressively larger particle sizes, the overall heat transfer coefficient decreased.

The effective operating bed height decreased with larger particle size, which caused a decrease in the overall heat transfer coefficient. The bundle overall heat transfer coefficient did not decrease until the effective operating bed height began to drop below the top of the tube bundle. The decrease was linear with decreasing bed height. The highest tubes showed the greatest decrease in overall heat transfer coefficients, while the lowest tubes showed little or no change. In addition, it was observed that the shallow beds expanded more than the deep beds, which resulted in a less dense medium for heat transfer to the bundle tubes when operating with a shallow bed. The heat transfer coefficients for the tubes in the lower third of the bundle were plotted as a function of specific pressure drop through the bed. It could be seen that there is no strong effect of specific pressure drop for the ranges obtained on the heat transfer coefficient.

For each of the tests the outside (bed side) heat transfer coefficient was also calculated and reported.

Computer programs have been written to calculate the gas dust loading from isokinetic data and the expanded bed operating height from bed pressure drop data. The isokinetic program has been debugged and checked against previous isokinetic data reduction calculations.

A new program was written to calculate the mass fraction of coal, coke, coal ash, limestone, calcined limestone, and sulfated limestone, in either bed material or fly ash, based on assayed fractions of carbon, hydrogen, sulfur, ash and loss on ignition. Another new program was written to calculate particle size distributions using any combination of U.S. Sieve screen sizes from 3 to 400 mesh.

Plans have been formulated to install two materials test racks in the multicell fluidized-bed boiler containing bar specimens of different materials. One rack is to be installed in the bed and one rack in the freeboard above the bed. In preparation for the test program, the recent technical literature on corrosion and erosion in fluidized-bed combustion and incineration was surveyed.

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II. ENERGY CONVERSION ALTERNATIVES STUDY (ECAS)

LEWIS RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CLEVELAND, OHIO

Contract No. E(49-18)-1751
Total Funding: $2,600,000

INTRODUCTION

The Energy Conversion Alternatives Study (ECAS) is being managed by the Lewis Research Center under the sponsorship of ERDA and the National Science Foundation, each of which is providing approximately one-half of the funds for the project. The studies are being conducted by General Electric Company, Westinghouse Electric Corporation, and a team of Burns & Roe and United Technologies, Inc., supplemented by Lewis Research Center laboratory personnel.

The overall objective of this project, initiated in August 1974, is to study advanced power generation techniques that can use coal or coal-derived fuels and to evaluate their relative merits and potential benefits. ECAS is to be conducted using a comparable basis of technology and materials performance and to evaluate these technologies in light of current conditions. In addition, ECAS is to define development plans for the various advanced systems, providing estimates of both cost and risk, and is to provide a basis for establishing needed technology or development programs. The evaluation of alternative systems on a comparable basis is needed so that cost-benefit analyses may be performed and the preferred systems selected for further development.

PROGRAM DESCRIPTION

Accomplishment of the ECAS objective requires a review of the technical claims, designs, performance, materials selection, development needs, and costs of each power generation system being studied. To determine the relative performance, economics, natural resource requirements, environmental impact, and development requirements and risks of the various advanced power generation systems, a *Conversion Systems Evaluation* is being used. This will be coupled with an *Energy Systems Evaluation* to assess the benefits and impacts of widespread implementation of these advanced energy conversion systems in electric utility applications. Basically, the project comprises four tasks:

- Task I—Parametric Analyses
  - 25 to 3000 MWe of generating capacity
  - Variety of coal or coal-derived fuels
  - Variety of heat rejection methods
  - Variety of combustors/furnaces
  - Variety of working fluids and thermodynamic cycles
  - Variation of major power generation parameters
  - Materials and performance related to technology status
- Task II—Conceptual Designs
  - Component conceptual designs
  - Plant layouts
  - Detailed estimates (performance, economics, environmental impact, natural resources for selected cases)
  - Construction requirements
  - Operating characteristics

- Technology advancements required
- Task III—Implementation Assessment
  - Preliminary research and development plans
  - Time and resources required to bring system to commercial service
  - Commercial acceptability
  - Special problems and limiting factors
- Task IV—Reports

A preliminary outline for reporting on the output of Tasks I, II, and III is shown below:

- Output of Parametric Analyses
  - Efficiency
  - Economics
    - Capital cost
    - Cost of electricity
  - Natural resource requirements
    - Coal
    - Water
    - Land
  - Environmental impact
    - Emissions (sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, particulates)
    - Thermal pollution
    - Wastes
- Output of Conceptual Designs
  - Plant layouts
  - Improved evaluation of plant characteristics
    - Efficiency
    - Economics (capital cost, cost of electricity)
  - Natural resource requirements
    - Coal
    - Water
    - Land
    - Critical materials
  - Environmental impact
    - Emissions (sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, particulates)
    - Trace elements
    - Thermal pollution
    - Wastes
- Output of Implementation Assessment
  - Development time and funding requirements
    - Preliminary research and development plans
    - Assessment of uncertainties and risks
    - Identification of key experiments and common technology
  - Factors affecting implementation
    - Economic viability
    - Environmental impact
    - Natural resource conservation
    - Reliability potential
    - Safety
    - Ease of operation, control, and maintenance
    - Limiting factors

Task I, Parametric Analyses, was completed during the second quarter of 1975. A variety of overall systems were studied, based on combinations of the following types of units:

Combustors: fluidized-bed, pulverized coal with scrubbers, and coal-derived liquid fuel; both atmospheric and pressurized; developing high-temperature and high-pressure steam as well as steam at normal conditions.

Power cycles: single gas turbine, combined gas turbine—steam turbine; open and closed cycle, with air-cooled, water-cooled, and ceramic turbines; supercritical carbon dioxide (Fehr) cycle; liquid metal Rankine topping cycle; organic liquid Rankine bottoming cycle; open and closed cycle including liquid metal magnetohydrodynamics.

Fuel cells: low-temperature phosphoric acid; low-temperature alkaline; high-temperature molten carbonate; high-temperature solid electrolyte. For these, clean liquid and gaseous fuels from coal together with integrated gasifiers were used.

Preliminary results of the parametric analyses, including a benefit and break-even cost analysis, indicated that potentially large dollar benefit may be possible for some of these advanced systems.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

The parametric analyses required for ECAS were nearly completed. However, so that completion of the report on this effort would not affect work on conceptual designs, the date for publication of the final report was delayed. The development of conceptual designs continued throughout the quarter. Some delays were experienced, however, because of delays in receiving fuel samples for determining semiclean fuel specifications. The samples were received during this period, but the equipment for filtering the fuel is still being fabricated and assembled.

Parametric Analyses

During the quarter, General Electric continued its effort to upgrade and complete the report on the Task I effort, and Westinghouse submitted drafts to Lewis Research Center for all but three Task I topical report sections. The materials advisory group finished its review and examination of the results of the parametric analyses. Lewis Research Center is reviewing the results of the Task I effort and is preparing the final report. Generally, so that completion of the report would not affect work on Task II, Conceptual Designs, the date for publication of the final ECAS Task I report was delayed.

Conceptual Designs

During this reporting period, Lewis Research

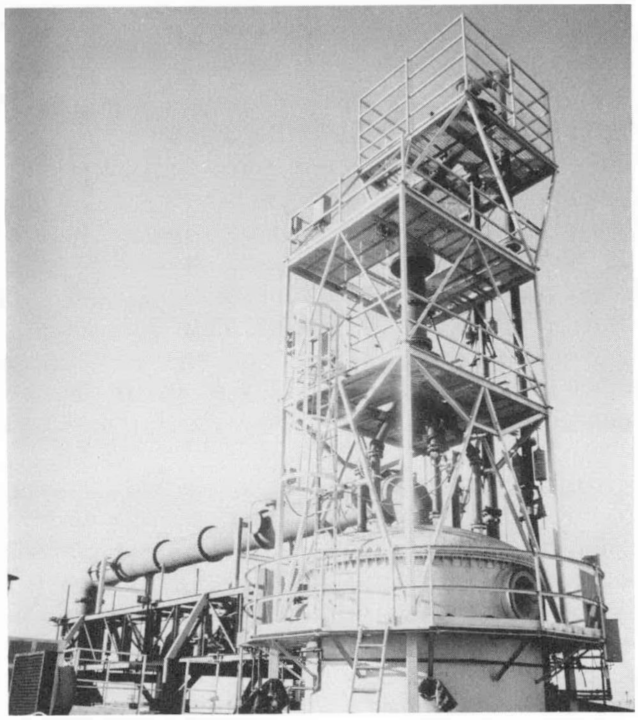
Center received four samples of H-Coal fuel for use in establishing the specification for semiclean fuel. One sample, filtered by Hydrocarbon Research, Inc., was sent to the Illinois Geological Survey Institute for trace element analysis and identification of the combined form of the alkali metals; 17 trace elements were identified and their concentrations determined. The remaining three samples will be filtered at Lewis Research Center using a high-pressure plate filter rig, which is being fabricated and assembled. Samples will then be sent to both General Electric and Westinghouse for their analysis. The third sample will be tested under Lewis Research Center cognizance at the Air Force Aero Propulsion Laboratory for electrical conductivity, thermal stability, and gravity.

General Electric continued developing conceptual designs of assigned systems. This effort included selection of the design point and configuration for the conceptual design of the liquid metal (potassium) Rankine topping cycle. The inlet turbine temperature will be 1,400° F, and the turbine exhaust will be used for heating feedwater for the high-pressure, high-temperature steam cycle. For the high-temperature closed-cycle gas turbine system, 11 parametric points were calculated, relying where possible on Task I data, and the design point and configuration for the conceptual design were selected. The turbine inlet temperature (1,850° F) was selected for a two-stage atmospheric fluidized-bed boiler with a closed-cycle gas turbine using helium and an organic bottoming cycle. A preliminary layout of the advanced steam, atmospheric fluidized-bed conceptual design was reviewed. Completion of the conceptual design of the water-cooled combined gas turbine-steam turbine cycle has been delayed because General Electric has not yet received a sample of H-Coal fuel from which to define the semiclean fuel specification.

Westinghouse established the final arrangement of the components of the gasification subsystem for the air-cooled combined gas turbine-steam turbine cycle with an integrated low-Btu gasifier. The overall heat balance for this plant was also completed, gas turbine engine cross-section drawings were prepared, and aerodynamic analysis was performed. In addition, the preliminary composite flow diagram, the plant island arrangement drawing, and the electrical diagram were completed. For the combined gas turbine-steam turbine cycle using semiclean fuel from the H-Coal process, Westinghouse completed as much as possible of the preliminary plant layout; the semiclean fuel specification has not been completed, however, because of delays in receiving fuel samples. Work on the advanced steam, pressurized fluidized-bed boiler was started. Discussions were held with the architect-engineer on plant layout and the effects of turbine backpressure on concept cost were evaluated.

Burns & Roe and United Technologies are continuing their work on the conceptual design of a molten carbonate fuel cell with an integrated low-Btu coal gasifier. This effort included a meeting with Lewis Research Center personnel to present and discuss the design point configuration selection. The design point is a 650 Mw plant with approximately two-thirds of this power output coming from the fuel cells and the remainder from a steam bottoming cycle. The overall powerplant efficiency is 50.5 percent.

III. PRESSURIZED FLUIDIZED-BED COMBUSTOR AND TURBINE POWER GENERATION



COMBUSTION POWER COMPANY, INC.
MENLO PARK, CALIFORNIA

Contract No. E(49-18)-1536
Total Funding: $3,465,780

INTRODUCTION

A combustor-gas turbine system is being developed by Combustion Power Company, Inc. (CPC), under the auspices of ERDA. This contract is an extension of an earlier research and development contract between CPC and EPA, in which municipal solid waste was burned without pollution in CPC's CPU-400 pressurized fluidized-bed combustion and gas turbine system. The overall objective of the current program is the development of a process to generate electrical energy from coal by applying technology based on pressurized fluidized-bed combustion of solid wastes and subsequent power generation. Specifically, CPC is tasked to expand existing CPU-400 technology to evaluate the combustion of high-sulfur coals mixed with dolomite, using a gas turbine directly on line for power generation, through laboratory research and long-duration testing of the process development unit. The schedule for development of this combustor-gas turbine system is provided in Figure III-1.

PROCESS DESCRIPTION

A schematic of the CPC combustor-gas turbine system is provided in Figure III-2. In this process, the coal is crushed to a size smaller than 1/4 inch. Dolomite is then added to the coal and the mixture is carried into the fluidized-bed combustor by means of a stream of compressed air. Fluidization is maintained by air from the turbine compressor.

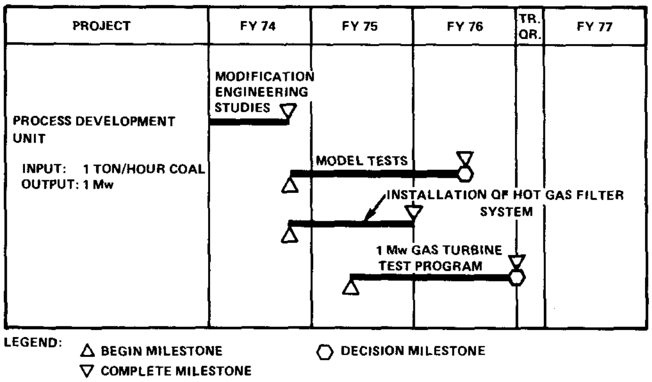


Figure III-1. COMBUSTOR-GAS TURBINE DEVELOPMENT SCHEDULE

In the fluidized-bed combustor, the coal is burned to produce gas; the sulfur compounds in the gas are absorbed by the dolomite. The gaseous products are passed through a three-stage system of separators to remove the solid particles. Stages 1 and 2 each consist of a pair of cyclone separators that remove particles down to 5 microns in size. The third stage, originally a system of inertial impactors, now consists of a moving-bed granular filter to remove particles down to 2 microns. The cleaned gas is then expanded in a gas turbine driving a 1 Mw generator.

To facilitate start-up, fuel oil is used initially to heat the fluidized-bed combustor to reaction temperature and is also used in an oil combustor during turbine start-up. The various transient modes of operation during start-up are controlled by a process control computer, which also records all process operating conditions.

There are several advantages to the CPU-400 system:

- Sizing is the only pretreatment of coal needed.
- High-sulfur caking coal can be burned without exceeding current EPA standards for sulfur dioxide and nitrogen oxide emissions.
- The only stack gas treatment necessary is removal of particulates.

HISTORY OF THE PROJECT

For the past seven years, CPC has been conducting a research and development program, under the sponsorship of EPA, to convert the heat energy of solid waste to electrical energy through the use of the CPU-400 system. With the cooperation of EPA, OCR contracted with CPC in June 1973 to conduct a research and development program to demonstrate the combustion of high-sulfur coal using CPU-400 technology.

Under the current contract, CPC has conducted parametric evaluations of coal combustion in a model of the CPU-400 combustor, using caking and noncaking high-sulfur coals. The caking coal used was Lower Kittanning seam; the noncaking coal used was Illinois No. 6. The coals were burned under varying conditions: superficial velocities of 4, 7, and 10 feet per second; bed temperatures of 1,400° F, 1,600° F, and 1,800° F; calcium-sulfur ratios of 1.5, 3, and 5; and three additives for absorbing sulfur compounds (two types of dolomite and one type of limestone). Each coal type was then tested for 120 hours at nominal operating conditions of 7 feet per second, 1,600° F, and a calcium-sulfur ratio of 1.5.

Next, CPC modified the CPU-400 system to provide the capability for coal and dolomite storage and feeding. This modified CPU-400 is known as the process development unit. Long-duration tests were planned in the process development unit using the data from the model experiments to determine and minimize exhaust emission levels of noxious gases and particulates. In addition, candidate turbine blade materials and coatings were installed in the turbine rotors and stators to evaluate erosion and corrosion effects.

The results of the tests indicated that both dolomites used were equally effective in suppressing sulfur dioxide, the relative effects of superficial velocities and bed temperatures were slight, and the optimum calcium-sulfur ratio was 1.5. Limestone was consistently 10 to 15 percent less effective than dolomite under all test conditions. The most serious problem encountered during the tests was that the separators installed in the process development unit were found to be inadequate to ensure acceptable turbine blade life or to meet current EPA particulate exhaust emission standards. To meet the stringent turbine exhaust emission requirements, CPC designed and installed a moving-bed granular filter.

Currently, CPC is operating the process development unit to test improved gas cleanup devices and the effect of coal combustion gases on erosion and corrosion of turbine and other hot gas system materials. Laboratory research,

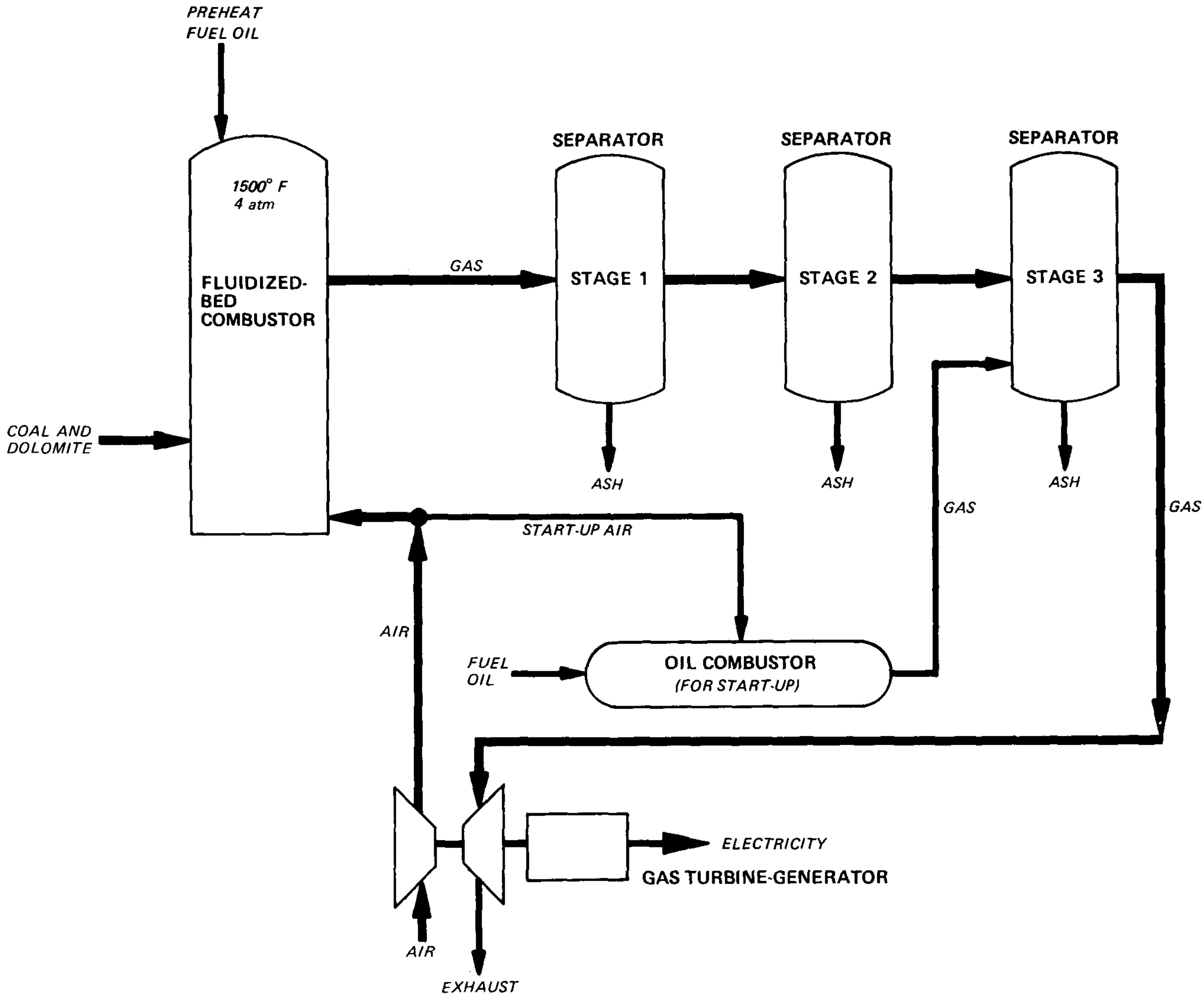


Figure III-2. COMBUSTOR-GAS TURBINE SCHEMATIC

including tests with the model combustor, is continuing.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

The moving-bed granular filter was installed in the process development unit and, after preliminary testing and adjustments, appeared to be performing well. Low-pressure circulation of the filter medium with the granular filter on-line was accomplished. A test was conducted to evaluate system heatup parameters but was terminated early because the inlet louver screen collapsed. In recent tests, higher corrosion rates have been occurring, possibly because of the use of a different coal with a higher phosphorous content. Analyses of the coal ash from these runs were inconclusive as to the source of the increased corrosion.

Analyses of the coal, cyclone ash, dolomite and turbine deposit specimens by Westinghouse are continuing. The turbine deposit analysis indicates that it is composed primarily of agglomerated sulfated dolomite fines. Tests were initiated as part of the baseline characterization needed to assess the influence of contaminants on scale structure in subsequent tests.

Process Development Unit

The results of two hot corrosion tests conducted during the third quarter of 1975 were reported this period. One of these tests (P403) was conducted in the process development unit; the other (M402) was conducted in the model system. In both tests, an inhibitor was added at the same weight ratio to the coal-dolomite mix. In the process development unit test, corrosion of the cascade specimens was not as severe as the corrosion of freeboard specimens, a reversal of expected results. While cascade temperatures were about 100° F higher than the freeboard temperatures, afterburning occurred in the first few run periods, implying the existence of a fuel-rich environment that would produce a more corrosive environment than in the cascade section. Thus, the level of suppression of the corrosive vaporous alkali salts in the process development unit was lower than that in the model system. Factors that may have contributed to the lower level of corrosion suppression in the process development unit were (1) local and momentary excesses of temperature or fuel, (2) insufficient reaction between the clay pigment inhibitor and alkali salts, and (3) the uneven mixing of coal and pigment.

The installation of the granular filter and modifications necessary to accommodate the filter were completed. Two probe assemblies for taking samples at high pressures from both the upstream and downstream sides of the filter were installed. A system of baffles was also installed to promote mixing of bypass air with the hot exhaust gases and to trap fractured particles of the filter medium before the stream enters the turbine. The entire circulation system was completed, with a storage hopper and a conveyor for the filter medium. In preparation for the test runs, the turbine was reassembled, the feeder valve in the coal feeding system reinstalled, and the computer program for process control revised to allow better control, better calculations of flow and pressure, and clearer display of on-line data.

Preliminary leak testing of the granular filter indicated that the gaskets relax over a period of time, resulting in a decrease in bolt tension. To seat the gaskets and arrive at operating torques in the shortest possible time, CPC initially over-torqued the bolts. Subsequent checks showed no leakage. The granular filter was filled with media, and low-pressure circulation was accomplished.

Test series P500 was started during this quarter to test the process development unit with the granular filter. The first test in the series, Test P501, was run to evaluate the system heatup parameters at 1,450° F. The run was prematurely terminated after 32.7 hours by the structural collapse of the inlet louver screen. Before the run terminated, several features relevant to operations were observed. Although the run was conducted using fuel oil instead of coal and samples taken, visual evidence indicated that the granular filter was filtering particulates from the hot exhaust gas. Termination and subsequent resumption of the flow of the filter medium through the circulation system was accomplished without difficulty. Pressure measurements indicated that the pressure seals were operating satisfactorily. Also, good distribution of the filter medium arriving through each of the six fill legs was achieved. The pressure drop across the filter was steady at the calculated value. The fill-and-drain system for controlling the flow of the filter medium presented difficulties, and modifications are in progress. Not only do volumetric changes during heating and cooling have to be considered, but also the special knife-edge gate valves installed in the fill-and-drain airlocks were found unreliable and subject to jamming by the small, extremely hard particles of the filter medium. Accordingly, a 33-cubic-foot reservoir is being designed for installation just below the deentrainment vessel at the top of the circulation system. Pulsed air jets will be used in place of mechanical valves to control the flow in and out of the filter vessel.

Laboratory Research

Preparations for Test M404 in the model combustor system included completing and mounting the specimen chamber between the fines return cyclone and the second-stage cyclone, locating reheat burners upstream and downstream of the granular filter, and locating a cascade section following the second burner. Changes in instrumentation were made to provide additional pressure and temperature measurements. The vapor collector tube was revised for air cooling rather than water cooling to reduce the tendency of water to condense on the surface of the vapor collector.

Test M404 was essentially a rerun of Test M402 D with precautions taken to avoid the temperature excursions that characterized the earlier test. The extreme corrosion penetration found on the Inconel 600, 601, and 690 specimens in Test M402 D were not experienced in Test M404. The visible penetration in other alloys was of the same general magnitude.

Generally, subsequent to test M402 B, corrosion rates have been higher than those experienced previously, which may reflect the change in the type of coal being used. Because of delays in receiving a resupply of the Illinois coal, a low sulfur, high phosphorous western coal was mixed with the Illinois coal. The phosphorous may have formed trace liquids on metal surfaces, promoting corrosion. There was no evidence, however, of these liquid formations in the bulk ash. Further analysis of ash samples taken during the test failed to resolve the phosphorous question. An increase in sodium concentration without a corresponding increase in the ratio of aluminum oxide and iron oxide over that in the coal, such as should result from the added clay, is a discrepancy to be further investigated. Sufficient supplies of the Illinois coal and Tymochtee dolomite have been received to finish all planned testing.

Test M405, with a planned duration of 1,000 hours, was started in November; by the end of the quarter, 678 hours had been completed. The nominal conditions for this test are a freeboard temperature of 1,600° F, a clay pigment corrosion inhibitor added at a rate of 0.4 percent by weight of the coal feed, and a calcium-to-sulfur mole ratio of 1.2. At the start of the test, three specimens of each of 22 alloys were being exposed in two locations, the combustor freeboard and the specimen holder between the first- and second-stage cyclones. (Test M405 was to have been conducted with reheat burners both upstream and downstream of the granular filter, followed by a cascade section to expose turbine-blade materials at high temperatures. There was not, however, sufficient oxygen in the exhaust gas to support combustion in the second reheat burner. Attempts to inject air for this purpose were unsuccessful; combustion was possible only when the coal feed was stopped and would cease as soon as coal feed was restored. Thus, the planned cascade-exposure tests cannot be conducted in the model combustor system.) After 464 hours of this test, one specimen of each alloy was removed from each location for examination. The extent of hot corrosion in these specimens was similar to that observed after 80 hours in the baseline test (M401), which indicates that the rate of attack has been significantly reduced by the clay pigment additive. For example, in the baseline test, the rate of attack on Inconel 738 was four times that found in M405. Some anomalies have appeared between the apparent sulfur "penetration" and the degree of surface attack. Further tests and analyses will be made in an attempt to resolve this problem.

Supporting Research

Analysis by Westinghouse Research Laboratories of the coal, cyclone ash, dolomite, and turbine deposit specimens from Test P403 indicated that the coal was rich in alkalis and the dolomite was low in alkali content. Inspection of the turbine deposit specimen revealed that it consisted mainly of sulfated dolomite. The deposits probably form when coal and dolomite are not being fed to the system and oil is being burned in the bed. Iron, aluminum, and potassium are present in the turbine deposit; vanadium, chlorine, and sodium are virtually absent. The concentration of coal trace elements in the turbine deposit is about one-fifth that in the cyclone ash, but the reason for this is not apparent.

After modification of the bench-scale tubular reactors, tests on turbine metal samples were initiated to establish baseline changes that occur in the absence of corrosive contaminants. The first preoxidation run yielded unsatisfactory results, possibly because of low oxygen partial pressure, contamination of samples during preparation, or interference between samples mounted closely together. The run was repeated with a modified cleaning procedure, an increase in the oxygen partial pressure, and a decrease of the carbon dioxide partial pressure. The even oxidation coating observed on the sample after 90 hours indicated that the test run was satisfactory. Specimens that were used to establish the baseline changes in bench-scale tubular reactions are being evaluated.

The spectroscopic technique used to measure alkali release from dolomites and coal ash was tested as a means of additive evaluation. The use of Tymochtee dolomite with a layer of kaolinite (1 to 1 by weight) reduced alkali release by approximately 90 percent. A dolomite and kaolinite mixture (4 to 1 weight) had even better alkali suppression. The alkali-ion gauge in use has demonstrated its effectiveness in measuring alkali metal removal by various absorbents. The sensitivity of the gauge is being improved.

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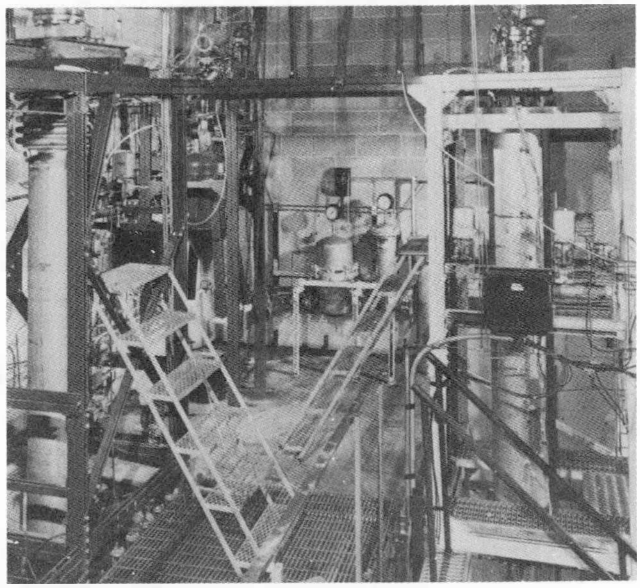
IV. SUPPORTIVE STUDIES OF PRESSURIZED FLUIDIZED-BED COMBUSTION



ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

INTRODUCTION

Pressurized fluidized-bed combustion is being studied by the Argonne National Laboratory (ANL) under the sponsorship of ERDA. This research and development program is being conducted to evaluate the feasibility and potential of fluidized-bed combustion at high pressures (up to 10 atm). The specific objectives are to:

- Optimize combustion procedures while maximizing retention of sulfur dioxide in the fluidized bed, minimizing the amount of nitrogen oxides in effluent gas, and increasing combustion efficiency.
- Evaluate the behavior and efficiency of the system when using different types of coal such as lignite and subbituminous.
- Study the levels of trace-element pollutants in the flue gas and the effects of process operating conditions on these levels.
- Determine the mechanisms of the various reactions in the process and how their thermodynamics and kinetics are affected when parameters are varied.

PROCESS DESCRIPTION

A schematic of the pressurized fluidized-bed combustor being used in the ANL test program is provided in Figure IV-1. The combustion unit has a diameter of 6 inches and is 11 feet long. The exterior is wrapped with electrical heaters to raise the bed temperature to coal ignition temperature and with cooling coils to regulate the bed temperature during coal combustion. Four additional

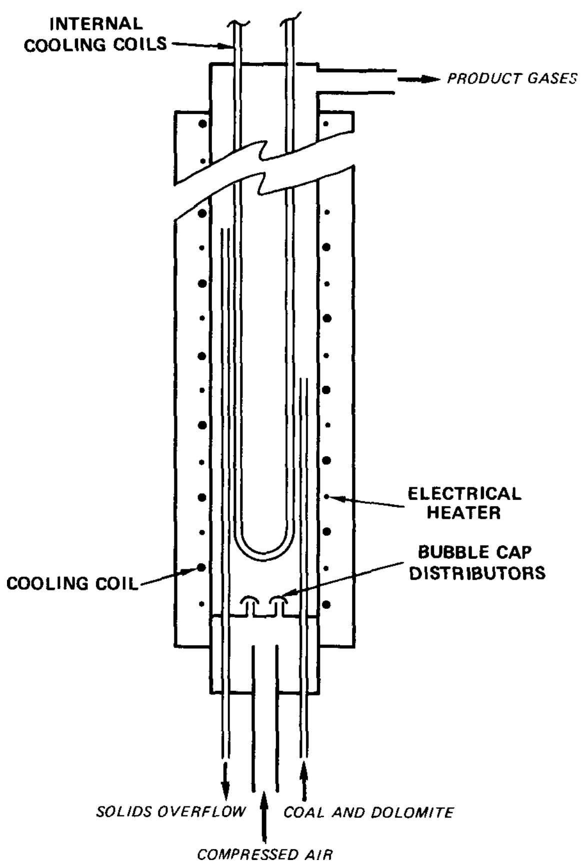


Figure IV-1. ANL PRESSURIZED FLUIDIZED-BED COMBUSTOR

hairpin coils for cooling are immersed in the fluidized bed. An internal overflow pipe is used for maintaining a constant bed level. The system is thoroughly instrumented and equipped with an automatic data-logging system.

Coal and dolomite are transported by an air stream into the base of the combustor. Compressed air for fluidizing the mixture is also fed into the base of the combustor. The coal is entirely burned in the fluidized bed of dolomite. The sulfur contained in the coal is released during combustion as sulfur dioxide, which is then absorbed by the dolomite. (The sulfated dolomite is regenerated for reuse in the combustor.) The gases produced must be mechanically cleaned, and can then be used to generate steam or to drive a gas turbine or in a combined-cycle process.

An advantage of the pressurized fluidized-bed combustor being developed by ANL is that nearly all of the atmospheric pollutants (mainly sulfur and nitrogen compounds) that are normally generated during the combustion of fossil fuels are removed from the effluent gas.

HISTORY OF THE PROJECT

Initial research and development of pressurized fluidized-bed combustion done by ANL included 11 experiments to measure the effects on a variety of dependent variables of temperature, fluidizing gas velocity, and ratio of the calcium content of the dolomite to the sulfur content of the coal. In these experiments, Pittsburgh seam coal was burned, at 8 atm, in a 3-foot-high fluidized bed and with 3 percent oxygen in the flue gas. The results indicated that:

- For calcium-sulfur ratios above 2.0, more than 90 percent of the sulfur dioxide was retained in the dolomite bed; the amount retained decreased as the calcium-sulfur ratio decreased.
- Nitrogen oxide levels were extremely low, ranging between 0.40 and 0.15 pounds of nitrogen dioxide per million Btu, as compared to the EPA emissions standards of 0.70.
- Combustion efficiency varied directly with combustion temperature, ranging from about 89 percent at 1,450° F to about 97 percent at 1,650° F. Unburned carbon elutriated from the bed was the major source of inefficiency.
- Additive entrainment varied directly with the superficial gas velocity, varying from about 5 percent at 2 feet per second to as high as 80 percent at 5 feet per second. The use of larger dolomite particles would have reduced entrainment considerably at the higher gas velocity.
- Values of heat transfer coefficients varied directly with gas velocity, ranging from about 40 Btu per hour per square foot per degree Fahrenheit at a gas velocity of about 2 feet per second, to about 115 at 5 feet per second.

ANL also conducted experiments using a subbituminous coal with a high ash content and a lignite with a low heating value. The operating performance of the fluidized-bed combustor in processing these western coals was excellent, thus demonstrating the versatility of the fluidized-bed concept for processing coals of widely varying rank and quality.

Another series of experiments was conducted to study the effect of combustor operating pressure on concentrations of nitrogen oxides and other noxious gases in the flue gas. In the absence of dolomite, the concentration of nitrogen oxide increased rapidly as the combustor pressure was reduced, going from less than 200 parts per million at 8 atm to around 1,600 parts per million at 1 atm. In the presence of dolomite, the concentration of nitrogen oxide also increased as the pressure decreased, but only to about 400 parts per million at 1 atm. In both cases, the sulfur dioxide concentration was relatively unaffected. Temperature (1,450° F to 1,650° F) had little or no effect on gas impurity concentration.

The distribution and potential emission of trace elements from fluidized-bed combustors were studied for comparison with available data from conventional coal-fired combustors. The elements of primary interest were lead, beryllium, mercury, and fluorine. Generally, the results indicated that the concentration of trace elements emitted from the fluidized-bed combustor may be significantly lower than that emitted from conventional coal-fired combustors.

Under the current program, ANL is continuing its experiments. Specifically, ANL is studying combustion and regeneration, including the chemistry of the ash-limestone mixture, limestone decrepitation, reaction kinetics, and gas pollutant levels; characterizing high calcium and dolomite limestones; and testing and evaluating materials of construction for fluidized-bed combustor and regenerator systems.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

Supportive studies of pressurized fluidized-bed combustion during the quarter included continuing research on combustion, sulfation and regeneration, and sulfur recovery and emission control. Emphasis in combustion studies was placed on initiation of an experimental program to evaluate the effects of recycling on sorbent performance and decrepitation. Among the sulfation and regeneration studies were continuing tests of α-alumina pellets impregnated with calcium oxide to determine their sulfur retention capability, their ability to be regenerated, and their integrity during fluidization. Oxides of barium, potassium, sodium, and strontium on α-alumina were also tested as sorbents. One-step regeneration experiments were conducted in the newly modified bench-scale regenerator. The extent of regeneration was improved, primarily because of the larger inside diameter of the regenerator which improved the length-to-diameter ratio of the fluidized-bed. This improved ratio in turn improved the quality of fluidization. Analyses of solid-solid reactions continued to be emphasized in sulfur recovery and emission control studies. Among other activities during the quarter were (1) additional experiments to determine the vaporization characteristics of trace elements in coal and their rate of volatilization and (2) experiments to gain a better understanding of the quality of fluidization and to correlate minimum fluidization velocities with the particle size distribution of the solids in the bed, bed temperature, and reactor pressure.

Combustion Studies

Two experiments were carried out to investigate the sulfur retention capability of lignite ash with high calcium content. These experiments duplicated operating conditions of a previous experiment except that alumina bed material was used instead of dolomite. The sulfur retentions calculated on the basis of flue gas analysis were 89 and 86 percent. These values compare extremely well with the value of 85 percent obtained in the previous experiment. Generally, the results of these experiments confirmed the premise that sulfur is retained by the ash during the combustion of lignite.

To check the operation of the combustor and analytical instrumentation and to verify the reliability of comparing current experiments with experiments performed previously, ANL duplicated four experiments. The results agreed very well with those obtained previously and established the experiments as a basis for comparison of the results of future experiments.

An experimental program was initiated during this quarter to evaluate the effects of recycling on sorbent activity and decrepitation. If the material should lose its reactivity for either sulfation or regeneration or if it should decrepitate severely after a limited number of cycles, the additive makeup rate would become sufficiently high that regeneration would not be justified. The first of these experiments, RC-1A, was performed using Tymochtee dolomite, which had previously been sulfated in the bench-scale combustor and regenerated in the small regenerator. When recycled to the combustor for this experiment the sorbent still contained about 4.3 weight percent sulfur. The experiment was performed intermittently over a period of several days, and about 120 pounds of regenerated sorbent was recycled. The chemical analysis of the solid samples from the test is not yet completed, but several limited observations can be made. Based on the flue-gas analysis for sulfur dioxide, sulfur retention was about 90 percent. The sulfur content of steady-state overflow and final bed samples was about 10.5 percent by weight, indicating that (1) utilizations were equivalent to those obtained during the first sulfation and thus that (2) the sorbent retained its activity for sulfur removal into the second cycle.

Sulfation and Regeneration Studies

Sulfation and regeneration of α-alumina pellets impregnated with calcium oxide continued. The pellets are being tested for their sulfur retention capability, their ability to be regenerated, and their integrity during fluidization. During this quarter, sorbents containing 16.5 and 20.9 percent calcium oxide in α-alumina were tested for the fraction of the calcium oxide converted to calcium sulfate as a function of time and for weight gain of a unit weight sample as a function of time. These data were added to previous data covering the range of 2 to 14.8 percent calcium oxide on α-alumina and of dolomite. Samples were heat treated at 2,000° F before testing at 1,650° F in an atmosphere of 0.3 percent sulfur dioxide and 5 percent oxygen in nitrogen. For calcium oxide loadings from 2 to 16.5 percent, the lower loadings approached complete conversion more rapidly. Higher loadings tended to absorb a greater amount of sulfur dioxide in a given period of time, particularly after the initial time period. The data for 20.9 percent calcium oxide was the exception to this trend. The approach to complete conversion occurred at a rate slightly better than the 14.8 percent sample. The amount of sulfur oxide absorbed in a given time period was the greatest of any of the synthetic sorbents, and two-thirds that of Tymochtee dolomite. The reason for the high sulfation rate is as yet unexplained.

Oxides of potassium, sodium, and strontium on α-alumina were tested as sorbents. Potassium and sodium oxide sorbents had higher rates of sulfation at 1,650° F than the calcium oxide sorbent, while the rates of sulfation of the strontium oxide and calcium oxide sorbents were the same. The regeneration rates for all metal sulfates were extremely high compared with their sulfation rates; a maximum of 5 minutes was required for regeneration, and regeneration varied from 85 to 94 percent. The instability of both the potassium and sodium oxide sorbents at the regeneration temperature of 2,000° F must be considered. Part of the weight loss observed during regeneration may have been caused by decomposition of the compounds.

An investigation of methods of producing supports with the required properties of surface area, porosity, and strength was initiated. Sulfation rates of calcium oxide in three different supports, Girdler T-708, Girdler T-375, and granular F-1 at 1,650° F using 0.3 percent sulfur dioxide, 5 percent oxygen in nitrogen were obtained. The Girdler supports were obtained from the Chemetron Catalyst Division and were to have the same properties. The low conversion of calcium oxide to calcium sulfate using T-375 cannot be explained since Chemetron has stated that the preparation techniques were identical. The granular F-1 support was prepared at ANL and showed the poorest performance. Boehmite was obtained from Alcoa and was heat treated to 2,000° F. A low sulfation rate was obtained. Since all of these supports were prepared from the same material, α-alumina, and sulfation is believed to be partly diffusion controlled, it was hypothesized that the observed differences in reactivity were related to differences in the porosity of the three support materials.

Porosity measurements on a variety of supports were started during the quarter. Results of the porosity measurements showed that the original material, boehmite, which is γ-aluminum oxide and hydroxide of high purity, has approximately 25 percent of its pores with a diameter larger than 0.04 micron. However, approximately 70 percent of the pore volume is the result of pores having diameters of 0.01 micron. After boehmite is heat treated for 8 hours at 2,000° F, it forms α-alumina (F-1) which shows approximately equal volumes of large ($>$0.1 micron) and small pores, but no pores with diameters smaller than 0.04 micron. If boehmite is heat treated for 8 hours at 2,250° F, a much greater number of large pores is observed; approximately 80 percent of the pore volume is the result of pores with a diameter greater than 0.1 micron. As the heat-treatment temperature is increased, the small pores coalesce into larger pores, which is desirable since this process possibly strengthens the material and provides the large pores needed for impregnation with calcium oxide.

The boehmite and heat-treated derivatives were impregnated with calcium oxide and then were tested for reactivity on the thermogravimetric analyzer (TGA). Most of the pores in boehmite are small; results showed that only a small amount of calcium oxide could be impregnated into this material. During sulfation, this sorbent performed poorly as a sulfur dioxide capture agent. The granular F-1 support that was heat treated at 2,000° F contained 8.8 percent calcium oxide; however, its sulfation rate was low. The F-1 support that had been heat treated at 2,250° F and contained 7.1 percent calcium oxide captured more sulfur dioxide than did the 6.6 percent calcium oxide in α-alumina (T-708) sorbent for any given residence time and also showed higher sulfation rates. Results showed that the rate of sulfation and the percent calcium utilization increased with increasing pore diameter. Porosity of other supports is being measured.

Barium oxide impregnated into α-alumina was sulfated and regenerated, then compared with the other metal oxide sorbents tested. The barium, strontium, and calcium oxide sorbents containing comparable amounts of metal oxides had the same sulfation rates. Since calcium is likely to be the least expensive material, it is probably the most desirable. The regeneration rate of barium oxide was observed to be only slightly lower than that for other sulfated sorbents when regeneration is with 3 percent hydrogen at 2,000° F.

One-step regeneration experiments continued throughout the quarter. These investigations of the technical feasibility of one-step reductive regeneration of sulfated sorbent were conducted in the newly modified bench-scale regenerator. The inside diameter was increased to 4.25 inches, and the metal overflow pipe was replaced with an external overflow pipe. The coal and the sulfated sorbent are now fed separately for independent control of feed rate to a common pneumatic transport line that feeds into the bottom of the reactor. A shakedown test was performed with a bed temperature ranging from 1,910° F to 1,970° F and a sulfated sorbent feed rate ranging from 7 to 12 pounds an hour. Tymochtee dolomite (11.1 weight percent sulfur) was fed at a rate of 11.5 pounds an hour into the bed, which was at a temperature of 1,945° F. The coal (Arkwright) feed rate was about 4 pounds an hour. It was assumed that the sulfur from all the feed coal was liberated as sulfur dioxide. When regeneration was calculated, this amount was subtracted from the total sulfur dioxide in the effluent. Based on the quantity of sulfur dioxide and hydrogen sulfide in the effluent, a sorbent regeneration of about 71 percent was calculated. The regenerated Tymochtee dolomite contained 1.8 weight percent sulfur and less than 0.1 weight percent sulfide.

A regeneration experiment (CS-5) using Tymochtee dolomite was performed in the bench-scale regenerator with in situ combustion of Arkwright coal. The results were compared with the results obtained in earlier experiments in which methane was combusted in situ. The experiments were conducted with a fluidizing gas velocity of about 3 feet per second, a solids residence time of about 30 minutes in the reactor, a temperature of 1,900° F, and a fluidized-bed height of 18 inches. The total reducing gas concentration in the effluent gas was about 4 percent for the experiment using methane and about 2 percent in that using Arkwright coal. In the experiment using methane, the sulfur dioxide concentration in the wet effluent gas was 1.3 percent and the particle regeneration was 38 percent, while in CS-5 they were 2.4 percent and 64 percent, respectively. In CS-5, hydrogen sulfide constituted 1.8 percent of the total sulfur in the effluent gas, and the sulfur released by the combustion of coal constituted 11 percent of the total sulfur in the effluent gas. The two experiments differed only in the kind of combustion fuel used and the bed diameter. Based on the flue gas analysis, the extent of regeneration in CS-5 was greater than in the earlier run. The improvement was probably not caused by differences in the fuel, but rather, because of the larger diameter in CS-5, the length-to-diameter ratio of the fluidized bed was smaller, which, in turn, improved the quality of fluidization. The quality of fluidization may play a very important role in the regeneration of sulfated sorbent since the regeneration reactions are relatively fast and good solid-gas contact is important.

Regeneration experiments using sulfated Greer limestone from Pope, Evans and Robbins were conducted with the reducing gas and required heat generated by the in situ combustion of Arkwright coal. In the first test (LCS-1), the experimental conditions were the same as for experiment CS-5. Comparison of results showed that the extent of regeneration was slightly better for sulfated limestone than for sulfated dolomite as estimated by flue-gas analysis for sulfur dioxide and hydrogen sulfide. The true extent of regeneration will only be determined after the chemical analysis of the regenerated particles has been completed.

An additional regeneration experiment (LCS-2) was performed using Greer limestone at the slightly higher bed temperature of 2,000° F, a feed rate of 12 pounds per hour, and a sulfur dioxide concentration in the wet flue gas of 2.8 percent. The extent of regeneration and the sulfur dioxide content of the flue gas were improved by increasing the temperature. A third test was conducted with a higher sorbent feed rate of 19 pounds per hour, a temperature of 1,940° F, a fluidizing gas velocity of 3.2 feet per second, and a total reducing gas concentration of 1.6 percent in the effluent gas. Comparison of results with the results of previous experiments indicated that, by increasing the sulfated sorbent feed rate (or reducing the solids residence time), a higher sulfur dioxide concentration in the effluent gas was obtained without greatly affecting the extent of regeneration. Because the regeneration reaction rates are relatively high, even greater solids throughput will be used in future experiments to investigate the feasibility of obtaining high sulfur dioxide concentrations in effluent gas streams.

The results of the chemical analyses from solid samples of these experiments are from 19 to 25 percent higher than those calculated by sulfur dioxide analyses of the flue gas. This discrepancy suggests the possibility that sulfur is being released in forms other than sulfur dioxide, hydrogen sulfide, carbon disulfide, and carbonyl sulfide, all of which were measured in these experiments. The extent of formation of elemental sulfur is being investigated.

The results of five experiments to determine the effect of temperature on sulfation and regeneration of Tymochtee dolomite were analyzed. As expected, higher temperatures enhanced the extent of regeneration of calcium oxide and sulfur from sulfated dolomite. As the temperature increased from 1,850° F to 2,000° F and the solids residence time remained constant or decreased, sulfur regeneration increased from 21 percent to 89 percent. In the five experiments, the sulfur dioxide concentration in the wet flue gas increased from 0.7 percent to 5.4 percent with increasing bed temperature. To evaluate the effect of temperature on the quality of the regenerated dolomite as a sulfur dioxide acceptor, the porosity of several samples was measured; the pore structure of the sulfated material was found to be plugged by sulfation. Since pores smaller than about 0.4 micron are relatively small and easy to plug, they do not contribute much to the extent of sulfation; rather, most sulfation takes place in the larger pores. These larger pores shrink during sulfation of calcium oxide by the changes in occupied molecular volume. As the regeneration temperature increased, the volume of the larger pores increased. However, the higher regeneration temperature of 2,000° F was not beneficial to the reactivity of the dolomite with sulfur dioxide. Although higher desulfurization reaction rates were obtained at higher regeneration temperature, the effect of temperature on the reactivity of the sorbent in subsequent sulfation cycles must also be considered.

Preliminary tests were performed to investigate the possibility that constituents of sorbents combine with coal ash during regeneration and form mixtures that have lower melting points than their constituents. The fusion temperatures of coal ash and mixtures were obtained by standard methods. Arkwright coal No. 2, a bituminous coal, was ashed and its ash fusion temperature was determined under oxidizing and reducing conditions. Under reducing conditions, the fusion temperature of Arkwright coal is very close to regeneration temperatures.

Coal ash was mixed with sulfated Tymochtee dolomite in different proportions, and the fusion temperatures of the mixtures were determined. As the ash content decreased, the fusion temperature of the mixture generally increased. However, with 50 percent and 90 percent ash content, the mixtures became fluid at approximately the same temperature, which suggested the possibility that, near the 50 percent ash content, an eutectic formed from constituents of the ash and sulfated dolomite. The fusion temperatures of mixtures of Arkwright coal ash and sulfated Greer limestone were determined; again, the possibility that a eutectic formed near the 50 percent ash content was suggested. The eutectic might have a fusion temperature lower than that found for the mixture with a 50 percent ash content, which could initiate the formation of agglomerates of sorbent and ash during regeneration.

Further studies have been made on the partial agglomeration of the sulfated sorbent which occurs at temperatures above 2,000° F in the one-step regeneration experiments. Study of agglomerated interior surfaces with an optical microscope revealed ash cenospheres. As gases evolve from the ash, these tiny glass-like beads are formed as tiny bubbles. X-ray diffraction analysis showed them to be amorphous. In recent experiments, agglomeration of sorbent and coal has occurred, even during mild temperature fluctuations caused by upsets in the regenerating environment at 2,000° F. Molten ash is believed to be responsible for the initiation of some of the agglomeration at these temperatures, and analyses are being performed to study this postulated mechanism.

Regeneration kinetic experiments of the one-step regeneration forces at temperatures near 1,900° F were carried out under mildly reducing conditions. A series of 11 runs was made in which sulfated Tymochtee dolomite was regenerated to the corresponding active sorbent. In these runs, ANL examined the influence of temperature, fluidized-bed height, fluidizing gas velocity, reaction environment, and feed rate. The 11 runs were correlated empirically for the establishment of a rate relationship. Specifically, two equations relating the reaction rates to the concentrations of methane and oxygen and the fluidized-bed height were developed. Based on the relationships, sufficient combustion gases must be introduced into the fluidized-bed reactor so that the desired temperature is reached and maintained and so that, at the same time, the gas velocity within the bed exceeds the minimum fluidization velocity but not to an extent that would hamper the formation of a bed in the fluidized state.

Sulfur Recovery and Emission Control Studies

During the quarter, additional work was done to determine if the solid-solid reaction, $CaS + 3CaSO_4 \rightarrow 4CaO + 4SO_2$, is feasible as a regeneration method. The extent of desulfurization of sulfated dolomite under various conditions was tested, removing the sulfur dioxide product by vacuum pumping. Fully calcined, sulfated dolomite particles were reacted with a stoichiometric excess of calcium sulfide at 1,830° F. On the basis of weight-loss data, it appears that the extent and rate of the reaction may be higher with the vacuum-roasting technique than with the nitrogen-purge approach, which was used in previous experiments.

Study of the solid-solid reaction, $3[CaSO_4 \cdot MgO] + [CaS \cdot MgO] \rightarrow 4[CaO \cdot MgO] + 4SO_2$, indicated that this reaction is a potentially feasible regeneration method. This conclusion was supported by TGA and X-ray diffraction analyses of the composition of sulfated and partially reduced stones. Kinetic experiments of this reaction, in which the starting material was prepared by partial reduction of the sulfated dolomite, showed that the calcium oxide content of the stones increased from 20 percent to 45 percent. The yield of the reaction was not as great as that obtained in some earlier experiments in which it was shown that the yield was dependent on the composition of the starting material. The rate of the solid-solid reaction was surprisingly high; the reaction reached 80 percent completion in less than 6 hours.

A second method of carrying out this reaction was studied, in which the sulfated material is reduced while the calcium sulfate-calcium sulfide reaction is occurring. This method requires that the reduction reaction be controlled so that its rate is in balance with the calcium sulfate-calcium sulfide reaction. The results of the initial experiments indicated that both reactions were occurring simultaneously when a reducing gas mixture containing less than 1 percent hydrogen was used. However, reducing gas mixtures of higher concentrations of hydrogen resulted primarily in the formation of calcium sulfide, showing that the reduction reaction was the dominant process. Yields of calcium oxide as high as 80 percent were obtained, indicating that it has potential technical application. This method also offers a means by which information on the reaction mechanism may be obtained.

Other activities in this area involved studies of rock particles of dolomite. When heated under a partial carbon dioxide pressure, dolomite particles are transformed into particles containing microscopic crystals of calcite and submicron crystals of magnesium oxide. These half-calcined particles can be used for the sorptive removal of sulfur dioxide in coal-fired furnaces. To study the changes that occur during the half-calcination process, ANL heated samples of 1337 dolomite under various conditions in a TGA to yield a series of samples containing various amounts of calcite. Polished sections of the treated samples were examined in reflected polarized light and compared with polished sections of untreated dolomite. The examination showed that dolomite crystals are transformed to calcite along grain boundaries, as well as within dolomite crystals. This suggests that greater efficiencies in the half-calcination process may be achieved by selecting fine-grained starting material from the quarry. Also, since sulfation is a surface-controlled process, partially transformed half-calcined samples might be more readily sulfated along avenues of fine-grained calcite than through a tight interlocking network of longer calcite crystals in completely transformed cycles. This will be tested by experiment.

Analyses of Trace Elements

Preparations for experiments to determine the presence of inorganic constituents in the effluent gas from coal combustion continued throughout the quarter. The objective of this study is to determine quantitatively which elements are present in the effluent gas and to differentiate between particulate and gaseous species. A work plan that includes a manufacturing plan, a test plan, and a quality control plan for fabrication of the laboratory-scale batch-type fixed-bed combustor to be used in these experiments was reviewed and approved. Fabrication of the combustor was well under way by the end of the quarter. The induction heating unit has been installed, tested, and found to be in good working condition. In addition, the specially ordered Kellundite filter to be used in the combustor for removing particulates from the hot combustion gases was received.

In the project to determine the vaporization characteristics of trace elements in coal, ANL analyzed the elements present in ashes prepared from Illinois Herrin No. 6 Montgomery County coal for seven temperatures ranging from 640° F to 1,810° F. The results showed unreasonably high concentrations of aluminum, nickel, manganese, calcium, and magnesium at 1,360° F and above, compared with those at lower temperatures. When the samples were reanalyzed using the X-ray fluorescence method, the higher concentrations were not observed, indicating that the previous analysis may have been of fault. The only nonmetallic element analyzed in the ash was chlorine, the concentration of which was shown to decrease significantly above 1,180° F. Trace amounts still remained in the high-temperature samples, however. In contrast to the nonmetallic chlorine, the metallic elements were generally retained in the ash up to 1,815° F. Under the oxidizing conditions present during the heat treatment of these ash samples, no loss in sodium or potassium was observed.

A second series of experiments to determine the vaporization characteristics of trace elements in coal was conducted. To obtain a more homogeneous ash for these tests, some 50 645° F ash samples were placed in platinum combustion boats and heat treated in a tubular furnace to temperatures between 1,560° F and 2,280° F for 20 hours in either an air or an oxygen-enriched air flow of 0.6 standard cubic foot per hour. The samples were then thoroughly mixed, resulting in a homogeneous ash. Measurements of the ash samples during heat treatment showed that the weight loss increased gradually with both the increase in temperature and the increase in oxygen concentration in the flowing gas. Analyses of the elements in the ash samples showed that iron, aluminum, sodium, potassium, zinc, manganese, and nickel generally remained in the fused ash up to 2,280° F under the oxidizing environment; the retention of these elements in the fused ash was not affected by the concentration of oxygen. Differences in the concentrations of aluminum on the one hand, and iron, zinc, and manganese on the other, in the ash samples used in the two series of tests are apparently the result of different methods used in preparing the coal samples. Some trace elements enter the coal samples from the grinding mills.

Fluidization Studies

Fluidization studies were conducted during this period to gain a better understanding of the quality of fluidization and to correlate minimum fluidization velocities with the particle size distribution of the solids in the bed, bed temperature, and reactor pressure. Experiments were run in the 6-inch diameter, 11-foot long pipe using a fresh, unsulfated dolomite bed with particle sizes ranging between 0.7 and 1.7 millimeters. Six runs were made with an average particle diameter of 1.2 millimeters, and 10 runs with 0.5 millimeter. The results show that the pressure drop across the bed varies linearly with the fluidizing air velocity until the minimum fluidization velocity for the partial bed is reached. At this point, there is no further increase in the pressure drop with air velocity for a while. Then the pressure drop increases more rapidly with the air velocity up to the point where the pressure drop is equal to the pressure due to the weight of the bed. At this point, the bed is totally fluidized and there is no further increase with the air velocity. The air velocity at this point is the minimum fluidization velocity for the total bed. From a graph of the pressure drop versus the fluidization air velocity, the minimum fluidization velocity can be obtained by extrapolating the straight-line relationship to the point where it crosses the pressure drop equal to that due to the weight of the bed. This intersection determines the minimum fluidization velocity for the total bed. The pressure drops at which fluidization was initially observed with the bed partially fluidized varies from 0.55 to 0.60 pound per square inch. Experiments were conducted with similar dolomite feed sizes and operating conditions, but with different mean particle diameters. When the mean particle diameter was larger, the percentage of the bed fluidized was smaller, segregation of material was greater, and fluidizing velocities for the partial bed and the total bed were larger. Results of the experiments showed that the fluidization velocities for the partial bed and total bed decreased in value as the pressure increased, in conformity with earlier experiments. In contradiction to the earlier observations, however, the fluidization velocity for the partial bed increased with temperature at a fixed pressure. A thorough search of the literature revealed that the prediction of minimum fluidization velocities for such beds is very complex, and that the method outlined above is the best for developing estimates.

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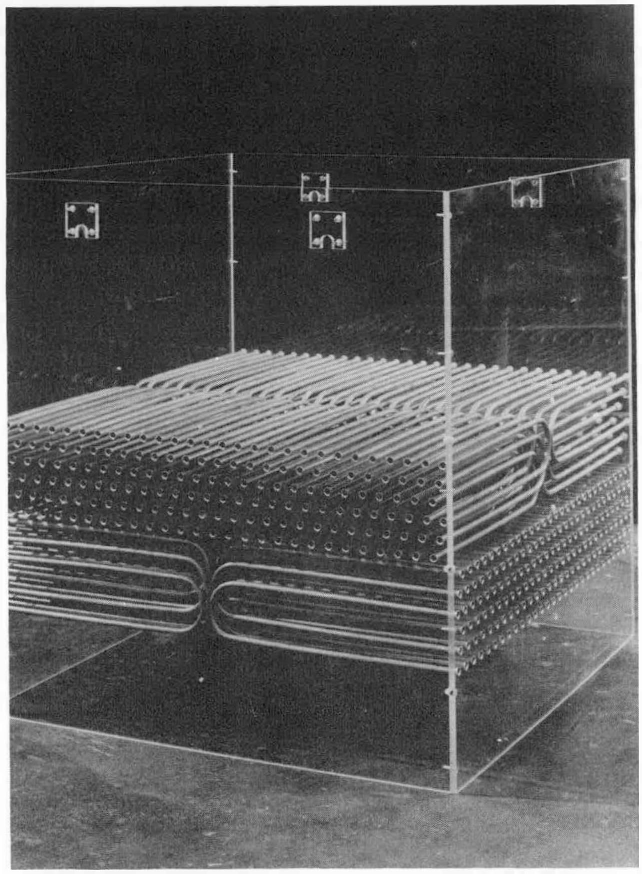
V. EXTERNALLY FIRED GAS TURBINE FOR MODULAR INTEGRATED UTILITY SYSTEM (MIUS)

OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE



INTRODUCTION

An externally fired gas turbine is being designed by Oak Ridge National Laboratory (ORNL) as part of the Modular Integrated Utility System (MIUS). ERDA and the Department of Housing and Urban Development (HUD) (under HUD contract 1AA-H-40-72) are the joint sponsors of this project.

The objective of MIUS is to provide services consistent with reduced use of national resources, protection of the environment, and minimized cost. MIUS might be sized to accommodate several hundred or a few thousand multifamily dwelling units, single-family units, and associated commercial facilities. MIUS is modular in that it can be located near appropriate users in phase with the actual demands of community development, as opposed to forecast of requirements. It employs an integrated systems approach in a total energy concept whereby some resource requirements of one service are met by utilizing the effluent of another. For example, heat rejected from a prime mover for heating buildings, processing potable water, operating absorption-type refrigeration units, etc., can be used, as can heat from solid waste incineration. In addition to conserving energy, MIUS should realize a savings in capital costs because long transmission lines and municipal sewers are not required.

ORNL's contribution to this project is to conduct a multiphase research program to develop one or more coal-fired power plants for use in a MIUS demonstration project. These phases include preliminary evaluation of the concept; design of a coal-fired power plant that can be used in the small total energy system envisioned, each module of which will have a capacity of about 0.5 Mw; and construction, operation, and evaluation of the plant. In conjunction with this project, ORNL has a continuing research program. The development schedule for this program is shown in Figure V-1.

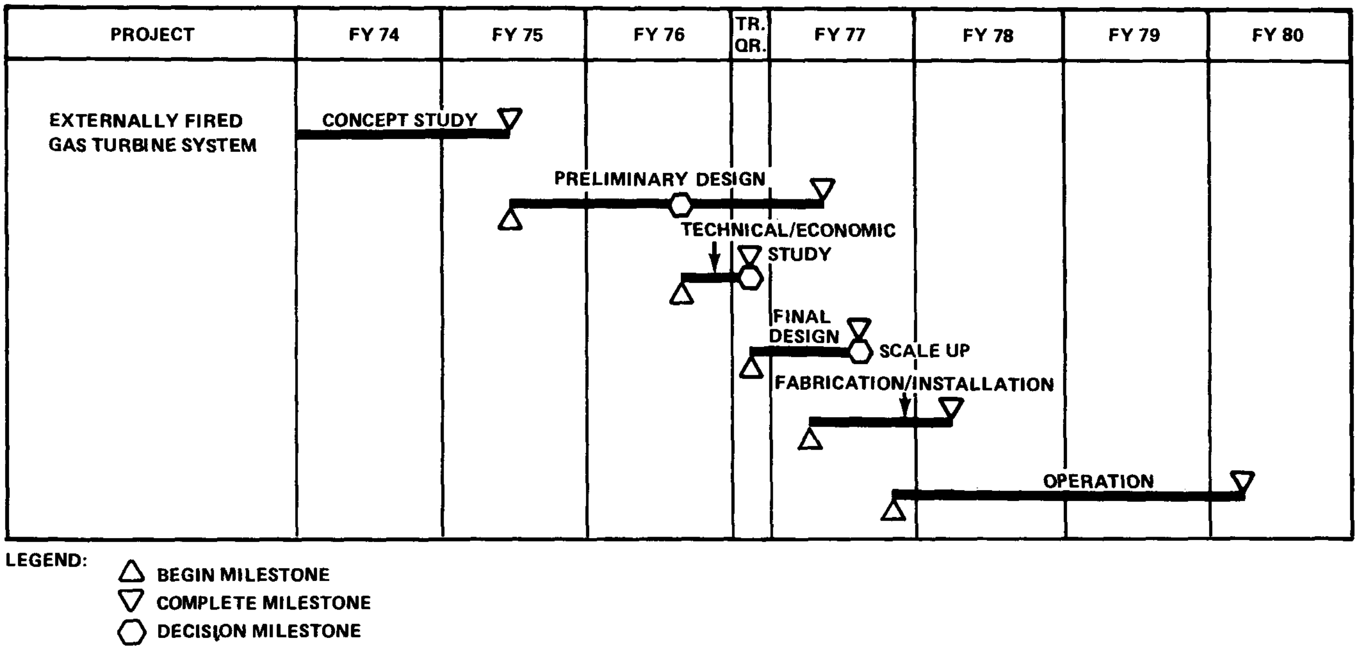


Figure V-1. COAL-FIRED TURBINE FOR MIUS PROGRAM SCHEDULE

PROCESS DESCRIPTION

For MIUS operation with coal, ORNL is designing a fluidized-bed combustion system combined with a closed-cycle gas turbine. A vertical sectional drawing of the proposed combustor is shown in Figure V-2. The design must provide for efficient operation at less than peak load since this will be the normal operating condition. As currently designed, the fluidized bed in the combustion system is composed of coal and limestone. The function of the lime is to absorb sulfur from the burning coal. Calcium sulfate is formed in the fluidized bed, making it unnecessary to remove sulfur oxides from the stack gases. The bed is about 20 inches deep. Preheated air enters a plenum chamber under the bed, flows up through the bed, through a plenum chamber over the bed, and then through the economizer region. The plenum chamber over the bed allows particles thrown up from the bed an opportunity to decelerate and fall back into the bed. The superficial velocity of combustion gases can be varied from 2 to 4 feet per second. The air for the bed furnace is preheated by a heat generator consisting of a stationary heat transfer matrix, with the hot stack gas flowing through one portion where the heat is transferred from the gas to the solid matrix. The particle movement in the fluidized bed promotes good combustion of the coal particles and provides excellent heat transfer coefficients with combustion gases. The bed temperature is maintained at about 1,600° F by air tubes about one-half inch in diameter welded into manifolds at the top and bottom. This configuration provides sufficient heat transfer surface area to remove the appropriate fraction of the heat of combustion.

The temperature through the entire closed-cycle system is kept relatively constant and its power output is changed by varying the basic pressure in the system. Current parametric studies agree with previous analyses; namely, the optimum pressure ratio for a closed cycle with recuperation is between three and four to one. A conventional, plate fin heat transfer matrix is used for the recuperator. A larger fraction of the heat of combustion goes into the air heated by the fluidized bed and a smaller fraction goes into the waste heat boiler, operating at 250° F. (The waste heat boiler simplifies both the fabrication and control problems.) For good cycle efficiency, the compressor inlet temperature should be 80° F if a standard outside air or cooling water tempera-

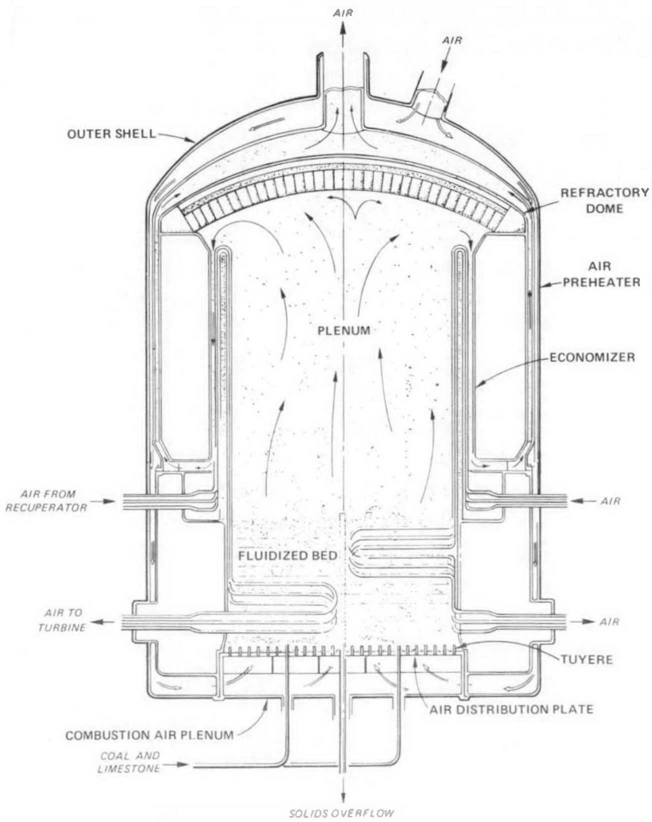


Figure V-2. FLUIDIZED-BED COMBUSTION SYSTEM FOR MIUS

ture of 60° F is maintained. A fan is currently included to reduce the backpressure on the turbine and increase the thermal efficiency.

Particulates in the stack gases must be removed. Two stages of cyclone separator remove fines of 10 microns and larger. If the gases are cooled to below 600° F, the bulk of the remaining fines can be removed with porous bags made of glass cloth.

The MIUS coal-fired gas turbine process has several advantages. For example, it provides the required overall thermal efficiency at full load, with little degradation in thermal efficiency for part-load operation, the more common operating condition. Furthermore, the fluidized-bed combustion system operates well with liquid or gaseous fuel, including char, low-sulfur coal, or solid organic waste; hence, it could also be used as an incinerator. In addition, keeping combustion at about 1,600° F prevents the formation of appreciable amounts of nitrogen oxide and keeps the ash temperature below its fusion point, so there is no difficulty with the formation of clinkers or glassy cinders.

ORNL has given much attention to basic problems such as (1) the uneven distribution of coal and limestone across the fluidized bed, (2) bed pulsations and tube vibrations, (3) decrepitation rates and reactivities of various limestones and dolomites after recycling, (4) the upper limits of gas velocity and bed depth, (5) the possibility of excessive corrosion on the combustion gas side of the tubes, and (6) the effectiveness of fly ash removal equipment.

HISTORY OF THE PROJECT

HUD foresaw the impending energy shortage and enlisted the assistance of ORNL in an investigation of total energy systems for use with new building complexes as a part of the MIUS program. ORNL assisted HUD first by looking at the problems of supplying heat to housing complexes from district heating systems tied to central stations and subsequently by examining various aspects of small total energy systems. Hundreds of these systems, employing diesel or gas engines or gas turbines, are in use currently in the United States and have proved to be economically attractive. When shortages of gas and fuel oil began to develop in 1972, HUD asked ORNL to investigate the possibility of developing a small total energy system that would operate with coal as the fuel, particularly with high-sulfur coal which is readily available. This led to the formulation of a program in May 1974, funded by OCR (now part of ERDA), to be carried out at ORNL through HUD.

Phase I of this program, concept and preliminary evaluation, entailed the comprehensive review of a wide variety of ways of employing coal in small total energy systems for HUD applications. Completed in July 1974, Phase I concluded that one promising way to use coal as the energy source for MIUS application is to burn it in a fluidized bed of limestone to produce air for expansion in a closed-cycle gas turbine. The thermal efficiency of the closed-cycle turbine is sufficiently high under part-load conditions, at which MIUS normally operates, to produce power that is competitive with power generated by utility companies, insofar as cost is concerned. The closed-cycle system can convert about 30 percent of the energy in the fuel to electricity and about 60 percent to heat, either as steam at 250 ° F or as hot water at 150° F.

Critical evaluations of the results of Phase I work were generally favorable. To supplement that work, an additional study of gas turbine bucket erosion, deposits, and corrosion was carried out, with particular emphasis placed on experience with coal-fired gas turbines. In January 1975, ORNL was authorized to proceed with Phase II, the development of a firm conceptual design and cost estimate for the construction of a system for test and evaluation. ORNL also has a continuing research and development program supporting this contract.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

During the fourth quarter of 1975, the contract for the design of the engine was approved. Modifications to the existing turbine-generators to adapt them for use in MIUS and the results of cycling tests were discussed with the contractor. The furnace design was revised during this period to reduce the number of flange joints and their sensitivity to warpage. Performance of the ceramic gasket material in tests was favorable; additional tests will be conducted to determine the effect of clamp pressures on air leakage rates. Laboratory research activities included installation of the coal feed and metering systems. Difficulties with the motor necessitated the purchase of a larger motor, which is now performing satisfactorily. The 4-foot-square cold-flow reactor performed as expected. This equipment was then modified and a second test was initiated.

Plant Design

The contract with AiResearch Division of Garrett Corporation was finalized in mid-October. This contract involves the adaptation of an AiResearch turbine to MIUS. AiResearch and ORNL employees met to discuss implementation of the contract. Possible modifications to the AiResearch Model 831-200 turbine to make it suitable for use by ORNL were also discussed. Of the six AiResearch engines now available, the best two will be selected by ORNL for use in the fluidized-bed coal combustion system. The noise level of the open-cycle engine was measured by AiResearch at 80 decibels, allowing normal conversation about 3 feet from the engine. The noise level of the closed-cycle engine would be lower because the air inlet, combustion, and exhaust noises would be minimized.

AiResearch has successfully brazed a completed module and improved air flow distribution by enlarging the outlet passage for high-pressure air. The results of cycling tests with the turbine-generator simulating truck operation in city traffic were encouraging. The module operated through 430 cycles, going from room temperature to 1,400° F in 8 seconds, before thin cracks developed in the leading edge of the brazed joints. The MIUS application will be much less severe; the peak temperature will be 1,100° F instead of 1,400°F, the power cycles will extend over many minutes instead of a few seconds thus reducing the rate of change in temperature, and the number of power cycles will be reduced from many per hour to about one per day.

AiResearch prepared new models for the analysis of the stability and control of the turbine-generator unit, and is supplying data on the detailed performance characteristics of the compressor-turbine-generator unit and the recuperator. These results are being used by ORNL to refine a computer program to yield more precise indications of expected turbine-generator performance.

Results of the first test of a flanged joint employing a ceramic gasket indicated that the leakage rate fell off to the equivalent of 0.15 percent of the combustion air flow from the total length of the flanged joints for the combustion air system. The unit was operated for 250 hours through 20 full thermal cycles with no increase in the leakage rate. New tests are planned using thicker gasket material and a range of clamping pressures to determine the effects of clamp pressures on leakage rates. These tests are being delayed pending receipt of the specimen for test purposes. An effort was made to reduce furnace costs by reducing the number of flange joints and their sensitivity to warpage that may occur as a result of thermal cyclings, and by reducing the requirements for dimensional tolerances. The resulting revised furnace design was discussed with three steel fabricators, which led to further design modifications. A full set of layout drawings has been prepared, and a 1/12-scale model is being built to be used in checking the assembly sequence. The model will also be used in discussions with potential fabricators to clarify the reasons for, and the latitude in, the dimensional requirements.

The request for a directive to proceed with procurement and construction was prepared and is being reviewed at ORNL. A "Request for Contract Action," a request for FY 1976 funds, was also prepared and includes a summary table of cost estimates and a bar chart showing timing of major steps in the program.

Laboratory Research

The laboratory space for the coal feed and metering systems was cleared and the equipment installed. In the initial test conducted, difficulty with the motor was experienced because of the much higher blower load when handling room temperature air than when handling the 400° F air for which the motor was designed. A larger motor was ordered, installed, and has been performing satisfactorily.

The Fire and Safety Department raised questions about the possibility of coal dust explosions in the bench test laboratory room. All equipment is being fitted with ground wires, and a report is being drafted justifying the safety of the installation of all equipment in the bench test work area. Estimates of the worst conceivable accidents that could occur will be included in the report.

The 4-foot-square, fluidized-bed cold-flow reactor was tested through most of the design operating range; the performance was consistent with the anticipated performance. Indications are that tube vibration frequencies vary from 8 to 16 cycles per second, depending on the air flow rate through the bed. There have not been any measurements of a large-amplitude vibratory motion. A new test was initiated after equipment modifications were made to allow investigation of the rate at which coal particles injected through the coal feed ports will be dispersed through the bed. Preliminary results are being analyzed.

VI. COAL-OIL SLURRY COMBUSTION PROGRAM

PITTSBURGH ENERGY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA

INTRODUCTION

The coal-oil slurry combustion program is being conducted by the Pittsburgh Energy Research Center (PERC) as part of a project jointly sponsored by ERDA and the Federal Energy Administration to study the economics and strategies for the use of coal-oil slurries. PERC is designing and constructing a liquid-fuel-fired Combustion Test Facility (CTF) similar to the one currently operated by ERDA for solid fuel research. This project will provide ERDA with an in-house capability to investigate a potentially near-term retrofit technology for increased coal utilization.

The specific objective of the CTF is to demonstrate the potential for using coal-oil slurries in a commercial oil-fired boiler without requiring extensive modifications or large capital expenditures for retrofit. Burner designs and system requirements must be developed and refined to permit the use of coal-oil slurries. In addition, coal-oil slurries will, in many cases, result in products with combustion characteristics different from those experienced when burning petroleum fuels. These fuel characteristics affect the design of feed systems, atomization and mixing of fuel with combustion air, air-preheat requirements, flame character and stability, and heat-transfer properties. (Slurry characteristics will be studied using a 100 hp firetube boiler.)

The CTF test program includes CTF shakedown tests, slurry combustion tests, slurry suspension stability tests, slurry erosion tests, slurry handling modifications and tests, slurry characterization tests, flue gas emission control tests, and an economic analysis on the use of various coal-oil slurries in retrofitted steam generating plants. The data will be used to design combustion systems using various slurries under process development for both industrial and utility boilers. In-house funding for this project was granted in July 1975.

PROCESS DESCRIPTION

The CTF consists of a 700 hp combustion test boiler, a closed-loop heat-removal system consisting of an air-cooled steam condenser and condensate unit, coal-oil slurry mixing and feed equipment, flue gas cleaning equipment, fuel storage facilities, and coal preparation equipment.

Initially, coal is unloaded into the coal storage bin, ground to 95 percent through 200 mesh (or an optimally defined mesh) in the coal pulverizer, stored in the coal supply hopper, and conveyed to a mixing tank by the coal feeder. Dust control equipment for the coal pulverizer includes a coal filter (cyclone separator and bag house) and a pulverizer blower. No. 6 oil is initially unloaded into a storage tank, then is heated to 100° F by a suction heater and conveyed to a mixing tank by the No. 6 fuel oil pump. The pulverized coal and No. 6 oil are blended into a slurry in a proportioning feeder tank. After mixing, the fuel is conveyed from the proportioning feeder tank to a slurry hold tank mounted on a weigh scale. The slurry feed pump then injects the fuel through a 300° F slurry preheater into the combustor. Enough air to burn the coal-oil slurry is supplied to the combustor from the combustion-air blower.

The hot flue gas from the combustor passes through a cooler to lower the temperature below the design requirements of the bag house. To reduce the sulfur dioxide level, sodium bicarbonate is injected into the stack gas before it enters the bag house. After particulate cleanup in the bag house, the flue gas is discharged to a 60-foot stack by the stack ID fan.

All the steam produced by the test boiler is condensed in an air-cooled heat exchanger. A condensate unit then pumps the liquid into a deaerator where the appropriate feedwater conditioning chemicals are added. The boiler feed pumps return the conditioned water to the boiler.

HISTORY OF THE PROJECT

When considering coal as an alternate fuel to oil, the difficulties of its direct use and the costs of converting oil-fired facilities are well documented. However, preliminary work has shown a potential for supplementing fuel oil with pulverized coal-oil slurries at a cost less than that of oil and requiring only minimum changes in existing boiler house equipment. Development of slurry as a fuel and of techniques for its use poses a short-term solution to restrictions on fuel oil supplies by reducing oil consumption by as much as 40 percent in applicable units presently firing oil. The specific markets identified are both large and small industrial units and the utilities.

The philosophy used in designing the CTF was to build around a commercial packaged boiler and auxiliaries to permit eventual industrial application of test results. However, the CTF will be supplied with extensive and sophisticated monitoring sensors and instruments, as well as an existing computer-controlled data-acquisition system, to allow on-line analysis and computation capabilities. The system will allow definition of the operating characteristics in the combustion of slurries with a minimum of experimental tests.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

Work on the coal-oil slurry combustion program focused on the completion of a preliminary shakedown test in a 100 hp firetube boiler using No. 6 fuel oil. Boiler efficiency was tentatively determined to be about 85 percent. Preparations for a 1,000-hour slurry test were nearly completed, and the first batch of slurry was mixed. The test will be started in January. In addition, about 90 percent of the facility bid package specification for the 700 hp watertube boiler was completed. Plant layout drawings were prepared for the coal-oil slurry preparation equipment, the CTF, and the flue gas cleanup system, and detailed drawings were prepared for seven major vessels.

100 hp Firetube Boiler

A preliminary test in the 100 hp firetube boiler, firing No. 6 fuel oil, was completed. The boiler was operated at rated capacity for approximately 24 hours. Boiler efficiency has tentatively been determined to be about 85 percent. This value may be altered slightly by a more precise fuel analysis which has not yet been received. Results of the test will be used as a baseline to which later slurry tests may be compared. The test also served to shake down the newly installed burner and oil feeding components. A motor used to drive the fuel metering pump was found to be defective and has been repaired.

Preparations for the 1,000-hour slurry test are being completed. The first slurry batch has been mixed, and the test will be started in early January. Coal is being pulverized in the coal handling system of a 500-pound-per-hour furnace being used in a Solvent-Refined Coal (SRC) combustion test program (Section VII). A schedule was prepared to permit preparation of enough coal for completing slurry studies without interfering with the SRC program.

700 hp Watertube Boiler

About 90 percent of the facility bid package specification was completed. Plant layout drawings were prepared for the coal-oil slurry preparation equipment, the CTF, and the flue gas cleanup system. Detailed drawings were prepared for seven major vessels. The process control instrumentation and general electrical specifications were prepared. The complete facility bid package specification should be completed by mid-January, at which time it will be submitted for procurement action.

The request for contract action, the technical proposal, and the management plan for this project are being reviewed by ERDA.

VII. SOLVENT-REFINED COAL (SRC) COMBUSTION TEST PROGRAM

PITTSBURGH ENERGY RESEARCH CENTER

PITTSBURGH, PENNSYLVANIA

INTRODUCTION

Combustion tests on Solvent-Refined Coal (SRC) are being done by the Pittsburgh Energy Research Center (PERC) as part of an ERDA program to increase coal utilization. SRC is a reconstituted material that has been dissolved, filtered, and separated from its solvent. The product is low in sulfur and ash, which allows compliance with environmental regulations. Although the process of solvent refining is apparently well defined, there has been no effective evaluation of SRC as a utility boiler fuel. The specific purpose of this PERC project, therefore, is to study the handling, pulverizing, burning, and fouling characteristics of SRC.

PROCESS DESCRIPTION

The SRC combustion test program is being conducted using a multiburner, water-wall furnace designed to burn pulverized coal at a nominal rate of 500 pounds per hour. The SRC being used in this project was obtained from a 6-ton-per-day SRC pilot plant in Wilsonville, Alabama. The SRC was produced from a high-sulfur Illinois coal, contains 0.8 percent sulfur and 0.3 percent ash, has a heating value of 15,400 Btu per pound, and has a fluid temperature of less than 300° F.

The SRC is air dried, transported to a feed hopper, then delivered to a pulverizer by a screw feeder. The fuel is pulverized in an impact mill with integral classification. (Earlier studies were made using hammer mills and ball-and-race type mills, with little success. The problems were generally related to generation of heat in the pulverizing process which caused the SRC to soften and agglomerate in the mills. The difficulties could possibly be overcome by rather strict temperature control of the material in the mills.)

After being pulverized, the SRC is pneumatically transported to a recycle loop. The recycle loop, inserted in the primary air-fuel transport line, minimizes fluctuations in the primary air-fuel ratio. The fuel is then burned in the direct-fired system through four burners in the front wall of the rectangular furnace (7 feet wide, 12 feet high, and 5 feet deep). The burners are designed to impart swirl in both the primary and secondary air streams.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

Because early SRC combustion tests resulted in sticking and eventual clogging of burner passages (the SRC was too hot), new burners were designed and fabricated to minimize the contact of SRC with hot metal surfaces. In combustion tests with the modified burners, satisfactory combustion results were achieved without appreciable deposit formation or burner fouling. To optimize recirculation and flame shape to overcome burner fouling, swirl in the secondary air stream was reduced and a longer flame established. Although flame temperatures obtained with SRC were several hundred degrees higher than those obtained with bituminous coal, the emission of nitrogen oxides was considerably lower than that obtained with coal fired through the more conventional burners originally used in the combustion system. Carbon conversions exceeded 99 percent, which is similar to the conversion obtained when bituminous coal is burned.

Combustion Tests

Early SRC combustion tests resulted in sticking and eventual clogging of burner passages because the SRC was too hot. To minimize the contact of SRC with hot metal surfaces, new burners were designed and fabricated, with water cooling provided to all surfaces that contact the primary air-SRC stream. A water-cooled conical shield was added to protect the stream against radiation from the burner flame. In tests of the modified burners, satisfactory combustion results were achieved without appreciable deposit formation or burner fouling.

The shield also provides a means of adjusting burner port velocity. Optimum velocity appeared to be 100 feet per second, achieved when the face of the shield projects 1/8-inch beyond the burner mouth.

The carbon conversions obtained in the SRC combustion tests exceeded 99 percent, which is similar to the conversion obtained when bituminous coal was burned. This conversion was achieved at excess air values ranging from 20 to 40 percent.

During the combustion tests, the swirl in the secondary air stream was adjusted to determine the optimum recirculation and flame shape to overcome burner fouling. When a high degree of swirl was imparted in secondary air, a short, bushy flame was produced, which resulted in deposits and plugging. However, as swirl was reduced and a longer flame established slightly detached from the burner, plugging was eliminated. Flames were brilliant yellow, with temperatures of about 3,400° F at the base of the flame, as measured by a two-color pyrometer. In comparison, the temperature of a similar coal flame was 3,150° F.

In spite of the high flame temperature and high nitrogen content of the SRC, the emission of nitrogen oxides from SRC combustion at 20 percent excess air (0.53 pound of nitrogen dioxide per million Btu) was considerably lower than that obtained from combustion of Pittsburgh seam coal at 20 percent excess air in the same furnace using the original burner design. (The *maximum nitrogen oxide emission* allowed in the Federal Stationary Source Performance Standards is 0.7 pound of nitrogen dioxide per million Btu.) Comparative combustion tests were conducted, firing a Pittsburgh seam coal, to explain the low emission of nitrogen oxides from SRC firing. When a coal flame was established similar to that of the SRC tests, a similar low nitrogen oxides emission was obtained. The emission from coal combustion at 20 percent excess air was nearly the same as that from SRC combustion at the same excess air level. As swirl was increased in the coal combustion tests, a short, compact flame was produced, which resulted in an emission of 0.8 pound of nitrogen oxide per million Btu, approximately the same as that measured when coal was fired with the original burners.

VIII. ANTHRACITE REFUSE UTILIZATION

MORGANTOWN ENERGY RESEARCH CENTER
MORGANTOWN, WEST VIRGINIA

INTRODUCTION

Anthracite refuse and silt bank materials are potential low-carbon, high-ash fuels resulting from mining and cleaning anthracite coal (principally in northeastern Pennsylvania). In the mining region, this refuse material is piled in a densely populated, geographically small area of about 480 square miles. The U.S. Bureau of Mines estimated that 800 banks containing 910 million cubic yards of refuse can be found within the anthracite mining fields. This material has been deposited from mining operations or from the reject streams of preparation and cleaning plants. Many of the banks contain refuse spanning the history of mining in the region. The deepest layers may have been deposited 100 years ago when preparation methods were crude, while surface layers have resulted from much better heavy media washing procedures and are essentially depleted in coal. Some of the older banks have been reworked using the better cleaning methods to recover coal; consequently the characteristics of the refuse varies widely from bank to bank or even within a given bank.

The Morgantown Energy Research Center (MERC) is examining the combustibility characteristics of these refuse materials in a fluidized-bed combustor. The value of this refuse as a fuel is important in the anthracite region because of the decline in mining in the area, which has led to a growing dependence on oil. Currently, the refuse banks are aesthetic eyesores that have supplanted valuable land from other uses, along with posing potential health and safety hazards from spontaneous combustion. The burning of this material in fluidized-bed combustors would provide fuel in a region that needs fuel, along with reducing some of the problems presented by the refuse banks.

PROCESS DESCRIPTION

The MERC atmospheric pressure fluidized-bed combustor is basically a refractory-lined cylindrical combustor of 18-inch internal diameter in the bed region, with an expanded freeboard cross section of 24-inch diameter. The combustor is equipped with a horizontal, water-cooled heat exchanger submerged in the bed and a separate water-cooled tube bundle in the freeboard to reduce exit gas temperatures. To control temperatures with the low-heating-value refuse fuels, six hairpin loops of 1/4-inch 310 stainless steel pipe with individual water flow controls were installed.

Fuel is pneumatically injected into the base of the combustor with room temperature air. Fluidizing air is provided through a plenum that feeds a number of orifices in the conical distributor. The reject solids that are separated from the exit flue gas by the primary cyclone can be reinjected into the bed with an air injector for carbon burnup. Flue gases are further cleaned by the secondary cyclone and parallel bag filters before exiting through the stack. Gases are sampled for on-line analysis at the exit of the combustor. Excess spent bed material is withdrawn through the apex of the inverted conical air distributor with a screw feeder.

An operating period with the combustor typically lasts 5 days, 24 hours per day. Start-up begins by preheating the empty combustor vessel with a premixed natural gas-air flame through the air distributor. When operating temperature is reached, the fluidized bed is built by feeding either 50-50 mixture (by weight) of anthracite coal and inert material (as limestone) or with the refuse directly. When the planned bed depth has been achieved, the natural gas flow is curtailed and the temperature of the bed stabilized by adjusting water flow in the submerged heat exchanger followed by reinjection of the primary cyclone ash. The complete start-up procedure requires 2 to 4 hours from cold lightoff to stabilization of temperatures with normal feeding of refuse and reinjected ash.

HISTORY OF THE PROJECT

Two anthracite refuse materials with widely different characteristics have been burned to date. These include a fine silt refuse from the Powderly Bank, south of Scranton, Pennsylvania, and a much lower quality material from a reworked bank north of Scranton, the Mid-Valley Bank. These refuse materials represent two extremes of fuel quality. The silt approaches anthracite coal in analysis and heating value, while the reworked refuse bank is much poorer in quality, containing mostly slate and "bone" (a laminated coal/slate agglomerate of medium carbon value). Similar low-grade coal-related waste materials have been burned in fluidized-beds in England in the form of slurries, usually with a supplementary fuel required. The fluidized-bed combustor is well suited to burning such materials because of the inherent low carbon in the bed coupled with the good mixing and long residence times to burn the relatively unreactive carbon found in such waste materials.

The Powderly Bank silt combustion test demonstrated that this fine material can be handled at low velocities in the fluidized-bed combustor. The variability of these refuse piles also became evident with the procurement of this feed material. A preliminary sample indicated that the Powderly silt would contain 52 percent carbon and 39 percent ash (8,400 Btu per pound), but the bulk sample (5-ton load), obtained in the same vicinity as the preliminary sample, proved to be much better quality.

The burning of the Mid-Valley Bank refuse was a much more severe test of the combustibility limits for these low-grade fuels. In the first test burning this material, limestone addition was avoided to demonstrate that this high ash material would build and maintain its own bed. Based on the results from this first run, however, it was evident that some limestone would be required to meet sulfur emission limits.

Generally, the combustion tests with these two refuse materials have demonstrated satisfactory carbon burnout and smooth sustained operations. (Each presented its own unique operating requirements to achieve these results, however.) The results indicate that the fuel value in the refuse carbon can be easily recovered in a fluidized-bed combustor. Fluidized-bed combustors with waste heat boilers located near the supply of anthracite waste could recover the heating value contained in this reject material and reduce the demand for expensive and scarce fuels. The burning of the waste would also somewhat reduce the environmental impact of the refuse piles, although the ash would remain a disposal problem of somewhat reduced magnitude.

The question of emissions from the burning of the wastes is being studied in the current test program at MERC. Initial indications are that some sulfur capture with limestone or other sulfur acceptor may be necessary to meet emission standards even though the sulfur content in the waste is low. The specific question of how much (or how little) sulfur absorbent will be required with various grades of refuse is being studied.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

Two test runs were made in the MERC fluidized-bed combustor during the quarter. Anthracite culm material from the Mid-Valley Bank was burned. In the first run, the bed was built solely with culm material. So that the amount of sulfur dioxide released could be determined, no limestone was used. In the second run, moderate amounts of limestone were added to limit sulfur dioxide emissions. It was determined that lower amounts of limestone than used in the run could be used to regulate the emission of sulfur dioxide according to EPA standards.

Combustion Tests

The MERC fluidized-bed combustor was operated in two runs, burning anthracite culm material from the Mid-Valley Bank. The objectives of the first run were to build the bed solely with culm material and to maintain operating conditions without using limestone so that the amount of sulfur dioxide released could be determined.

The objective of the second run was to add moderate amounts of limestone to the equilibrium bed from the first run to limit sulfur dioxide emissions. MERC determined that, to regulate the emission of sulfur dioxide according to the EPA standard of 1.2 pounds of sulfur per million Btu, a lower rate of limestone addition than tested could be employed. This will be attempted during the next run, tentatively set for January 1976.

Major changes in equipment were made during the quarter:

- New panel boards were installed in the room adjacent to the fluidized bed. Most of the instruments and gauges have been installed and calibrated except for the sulfur dioxide and nitrous oxide analyzers, which are presently being calibrated. Also, flow control valves were installed for use on the control panel to regulate the unit, air, and gas flows on a more continuous and accurate level.
- Valves were installed on the pressure tap system inlet ports to avoid any loss of flow during operation.
- A weigh platform was installed and calibrated to weigh the amount of culm in the storage hoppers from the beginning to the end of the run so that the amount of solids being burned can be monitored more accurately.

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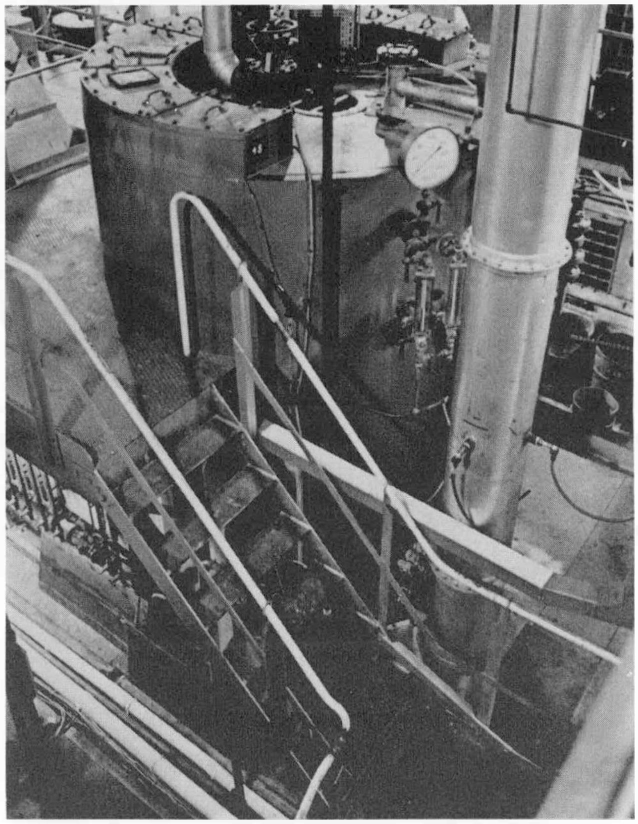
IX. PRESSURIZED FLUIDIZED-BED COMBUSTION RESEARCH



NATIONAL RESEARCH DEVELOPMENT CORPORATION

LONDON, ENGLAND

Contract No. E(49-18)-1511
Total Funding: $215,831

INTRODUCTION

The National Research Development Corporation (NRDC), in conjunction with the British Coal Utilization Research Association, Ltd. (BCURA), is studying pressurized fluidized-bed combustion under the sponsorship of ERDA. This research and development program is being conducted to assess the capabilities of pressurized fluidized-bed combustion from the point of view of minimizing pollution, especially from high-sulfur coals; avoiding excessive maintenance because of corrosion in conventional plants; and reducing capital and operating costs of electric power generating systems. The program enables ERDA to obtain combustor performance data on systems of substantial size (applicable to pilot plant design), while obtaining added research information. The specific purpose of this contract is to establish the effect on performance of (1) fouling of turbine blades, (2) emission of alkalis and sulfur and nitrogen oxides, and (3) bed behavior (clinker formation) at higher temperatures (1,650° F to 1,750° F) than previously used for this type of combustor (1,470° F). The data acquired will be combined with other data on fluidized-bed combustors and will be used as the design basis for a pressurized fluidized-bed combined-cycle plant.

PROCESS DESCRIPTION

A schematic of the pressurized fluidized-bed combustor being used in the NRDC test program is provided in Figure IX-1. The reactor, the principal component of the unit, has a distributor plate, but also has an immersed bank of water-cooled tubes for regulating the bed temperature. Baffle tubes (without cooling) are placed above

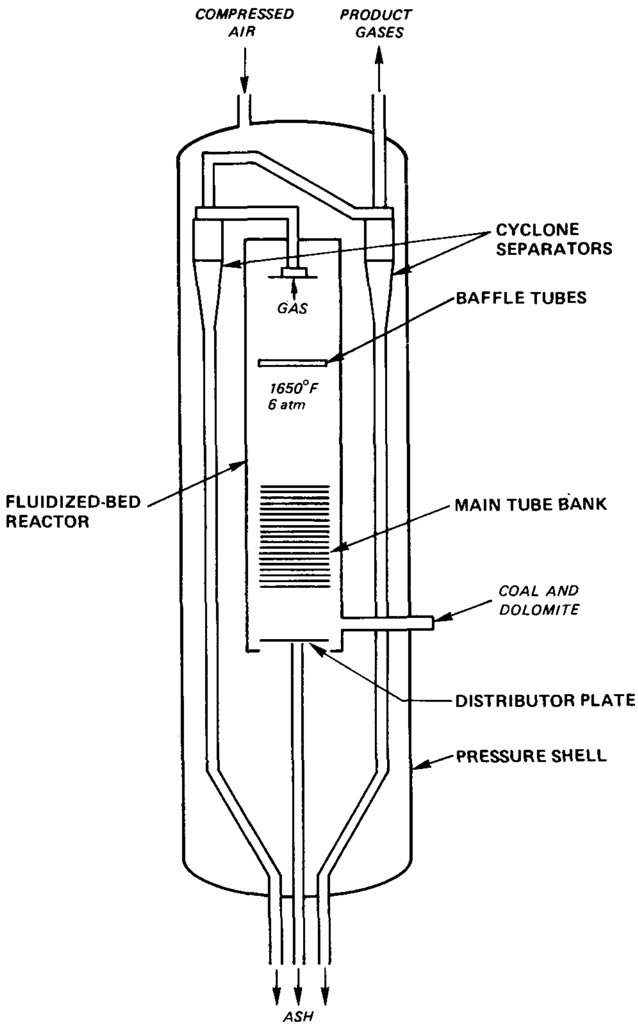


Figure IX-1. NRDC PRESSURIZED FLUIDIZED-BED COMBUSTOR

the bed surface for fluid dynamic stability. Another important component of the combustor is a two-stage system of cyclone separators. The reactor and separators are enclosed in a pressurized shell (which has an internal diameter of 6 feet) to eliminate stresses that large pressure differentials would generate on the reactor refractory. Pulverized coal, with dolomite added for removal of sulfur compounds, is carried to the base of the fluidized-bed reactor by an air stream. Pressurized air enters the top of the shell, flows around the internal components, and enters the base of the reactor through the distributor plate, where it is used as the fluidizing medium. The product gases are passed through the cyclone separators to remove entrained fines. The gas can then be used in a combined-cycle process.

HISTORY OF THE PROJECT

Early work done by NRDC/BCURA on pressurized fluidized-bed combustion involved 1,000 hours of test runs (1968 to 1971) at a bed temperature of 1,470° F, using Pittsburgh seam and some United Kingdom coals. The results of these tests indicated that turbine erosion and deposition were negligible and that sulfur emissions could be controlled by adding dolomite.

Under the current contract, beginning in August 1972, the combustor was modified to permit it to operate at higher temperatures. Four tests were conducted, with changes in combustor pressure, coal origin (Pittsburgh seam and Illinois), bed temperature (1,650° F and 1,750° F), and sulfur dioxide acceptor (dolomite and limestone). In these experiments, NRDC/BCURA found that:

- Combustion efficiencies exceeded 99 percent at 1,750° F and were only slightly lower at 1,650° F.
- Sulfur emissions for 3 percent sulfur coal could be limited to 0.1 pound per million Btu by adding dolomite at a calcium-sulfur ratio of slightly greater than 2.
- Nitrogen oxide emissions averaged about 0.2 pound per million Btu.
- Deposits on the cascade blades did not occur to a significant extent at bed temperatures of 1,650° F, but were sufficiently extensive at bed temperatures of 1,750° F to be a potential source of operating problems.
- The ash in the bed did not sinter or adhere to the walls under any of the operating conditions investigated.

The main conclusion from these results, with respect to minimizing emission of sulfur and nitrogen oxides, freedom of fouling or corrosion of turbine blades and heat transfer surfaces, freedom from sintered accumulations in the bed, and combustion efficiency, is that performance when burning Illinois and Pittsburgh seam coals at bed temperatures of around 1,650° F should be as good as the performance achieved in previous tests. The ability to operate at higher temperatures in a combined-cycle plant will result in a further saving in fuel (about 2 percent) and an extension in operating load range that can be achieved by varying bed temperature.

This test program (Tests 1-4) was completed in September 1973, and NRDC prepared a final report. In late 1974, the program was extended to include a fifth test to investigate fluidized-bed combustion at a bed temperature of 1,650° F and an excess air rate of 100 percent, with attention also directed to any primary or secondary cyclone depositions and to cascade erosion, corrosion, and deposition. In December 1975, a contract modification was approved to include a series of three fluidized-bed tests (Tests 6-8) to investigate the effect of various excess air rates, bed depths, and bed velocities on combustion efficiency, sulfur and nitrogen oxides emissions, and circulation. Additional construction materials will be tested for corrosion resistance.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

During the quarter, a contract modification was approved to include three fluidized-bed tests. Alteration of the equipment to accommodate these tests was begun.

Combustor Modifications

The contract modification approved in December expanded the scope of work to include an investigation into the effect of various bed depths (4 and 8 feet), excess air rates (20 and 100 percent), and fluidizing velocities (2.5 and 7 feet per second) on (1) fouling, erosion, and corrosion of a static cascade of turbine blades and of target rods; (2) emissions of sulfur dioxide, alkali, and nitrogen oxides; (3) bed behavior as regards clinker formation; and (4) combustion efficiency. Three tests will be conducted.

In order to perform the tests, the combustor and test rig must be modified. The following tasks were accomplished during this period:

- Details of the tube size and pitching in a new tube bank were determined, and an order for the tube bank was placed with Foster Wheeler Power Products Ltd.
- The associated combustor casings were designed and are being fabricated in BCURA workshops.
- A new tube bank assembly enabling predictions of heat transfer rates to membrane-wall type constructions was designed and fabricated, and will be installed in the walls of the combustor.
- The general layout of the bypass ducting was determined.
- An order was placed for the required quantity of Dolomite 1337.

X. HIGH-TEMPERATURE DUST CONTROL

CONSTRUCTION ENGINEERING RESEARCH LABORATORY
U.S. DEPARTMENT OF THE ARMY
CHAMPAIGN, ILLINOIS

Contract No. E(49-18)-1782
Total Funding: $67,302

INTRODUCTION

Under the sponsorship of ERDA, Construction Engineering Research Laboratory (CERL), U.S. Department of the Army, is to evaluate the efficiency of a Particle Precipitating Heat-Transfer Surface (PPHTS) device for removing dust particles from the high-temperature exhaust gas stream of a fluidized-bed combustor. The fluidized-bed combustor to be used in this project is a modified coal-fired boiler plant owned by ERDA. This plant is currently being operated for ERDA by Pope, Evans and Robbins, Inc. (PER), at a government-owned test facility in Alexandria, Virginia.

PROGRAM DESCRIPTION

The PPHTS evaluation project, initiated in July 1975, is to be completed in mid-1976. This project comprises several tasks:

- Design of the test apparatus and PPHTS test sections.
- Procurement of the necessary components and fabrication and installation of the apparatus.
- Calibration of the automatic particulate analyzer, flow monitoring apparatus, and pressure and temperature transducers.
- Development of procedures for data acquisition and reduction.
- Provision of assistance to PER during operation of the combustor in acquisition of the necessary data and performance of subsequent data analyses and summaries.

Design of the test apparatus was completed in August 1975. The apparatus will be placed on the roof of the Alexandria test facility and will connect to the exhaust gas stream of the fluidized-bed combustor. The configurations of the test sections include four collector rod angles (at constant rod shape) and two additional rod shapes (at constant rod angle to the gas stream). The six different sections will be tested in sequence. Each of the six test runs will be carried out during a period of 2 weeks.

The general experimental design involves measuring the dust load entering the test section and the amount of dust captured by the PPHTS collector rods in the test section. The dust will be collected in a dust hopper located below the test section. After each test, collector efficiency, defined as the ratio of the captured-to-incoming dust load, will be calculated. The shape and angle of inclination to the gas stream of the dust collecting rods in the PPHTS device will be varied to determine the effects of angle and shape on collection efficiency.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

To avoid interfering with PER's operation of the test facility, CERL modified the design of the test apparatus for measuring the velocity and dust load of the flue gas stream to include a venturi velocity meter and a manual stack sampler instead of automatic continuous monitors. Procurement of equipment is under way. However, because of problems in obtaining replies from subcontractors to requests for quotations on fabrication of the ductwork and the test sections, the fabrication and installation task is approximately 2 months behind schedule.

PPHTS Device Design and Construction

During the quarter, CERL revised the design of the test apparatus for measuring the velocity and dust load of the flue gas stream to avoid interfering with PER's operation of the test facility, which includes a venturi velocity meter and a manual stack sampler. Instead of an analyzer at the entrance to the test section, CERL will sample the exit stream from the test section and calculate efficiencies by measuring the outcoming dust load and the amount of dust captured through the collectors.

Procurement of equipment is under way. A visible emission monitor, Lear-Siegler Model RM-41, for determination of particulate emissions has been delivered. To prevent dust escaping from the dust hoppers under the test section back into the gas stream and then to the atmosphere, a dust determination assembly has been procured. Additional piping, pressure gauges, and valves have also been purchased.

A contract to fabricate dust collecting rods of aluminum was awarded to General Extrusions of Youngstown, Ohio. Two rod shapes will be extruded, with an extended length of 468 feet each. Requests for quotation for fabrication of the ductwork and the test sections were distributed, and responses are undergoing evaluation. Because of delays in the responses and some misunderstandings, the fabrication and installation task was approximately 2 months behind schedule at the end of the quarter.

XI. APPLICATIONS OF FLUIDIZED-BED COMBUSTION TECHNOLOGY TO INDUSTRIAL BOILERS

EXXON RESEARCH AND ENGINEERING COMPANY
LINDEN, NEW JERSEY

Contract No. E(49-18)-1798
Total Funding: $350,000

INTRODUCTION

Several coal conversion technologies, including direct combustion of coal in a fluidized-bed boiler, coal liquefaction, and coal gasification, are currently being developed. When implemented on a commercial scale, these technologies will greatly increase the utility of coal as a highly acceptable source of industrial energy. Of these technologies, fluidized-bed combustion offers the possibility of near-term implementation. Therefore, Exxon Research and Engineering Company is conducting a research project to study the diverse industrial applications of fluidized-bed combustion technology. This project is being sponsored jointly by ERDA, EPA (EPA Contract No. D5-E-767), and the Federal Energy Administration (FEA) (FEA Contract No. CO-04-50168-00).

The objective of this study is to conduct economic, energy, and environmental analyses of the industrial applications of atmospheric and pressurized fluidized-bed technology as a method of using coal to generate electrical power and process steam for in-plant use. Some advantages anticipated with fluidized-bed combustion technology are improved pollution control, high thermal efficiencies, reduced capital and operating costs, and the ability to use a wide variety of coal types. Fluidized-bed combustion systems are expected to surpass air quality standards for stationary source emissions.

PROGRAM DESCRIPTION

Accomplishment of the objective of this project, started in January 1975 and to be completed in June 1976, requires consideration of both new and retrofitted atmospheric fluidized-bed boilers with steam output capacities ranging from 10,000 to 500,000 pounds per hour. The effects of fluidized-bed combustion technology on each industrial sector as well as the composite for all industries and on each geographic region as well as the entire nation are being studied for 1978, 1980, 1982, 1985, 1990, 1995, and 2000. The project comprises several tasks:

- Determination of the applicability of fluidized-bed combustion technology for meeting industrial boiler requirements based on life-cycle cost, energy conversion efficiency, reliability, maintainability, stack gas emissions, waste disposal and utilization, required plant characteristics, fuel flexibility, and installation and operational problems.
- Development of estimates and confidence limits for the maximum degree of industrial application based, as a minimum, on fluidized-bed combustion technology characteristics, industrial sector specifications for boilers, boiler age distribution, and boiler replacement data.
- Assessment of the demand for fluidized-bed combustion technology, including consideration of the cost of fluidized-bed combustion

systems, prices of various fuels and their availability by region and by industry, capital availability, equipment production capabilities, environmental acceptability, industrial propensity to switch to new boiler design, competing technologies, and solid waste characteristics with respect to disposal and utilization. The assessment is to provide the sizes, numbers, and types of fluidized-bed boilers that will be required by industry type and region to satisfy the maximum, minimum, and most realistic projected demand.

- Determination of the impact that demand for and application of industrial fluidized-bed combustion technology will have on total national energy consumption and on reduction of fuel oil and natural gas consumption.
- Analysis of economic data, capital requirements, and operating costs of each component of the fluidized-bed combustion systems; calculation of the economic implications of fluidized-bed combustion applications; and comparison with the costs of other alternatives, such as the use of clean fuels in a conventional boiler.
- Determination of the effect of industrial fluidized-bed technology applications on air emissions, solid waste production, and effluents to water, and comparison with the environmental effects of other technologies and other fuels and industrial power and steam sources.
- Determination of specific technical requirements for representative industrial fluidized-bed boilers, based on the demand, economic, environmental, and technical analyses.

The analyses completed indicate that the potential for fluidized-bed combustion of coal was concentrated in the chemicals, paper, petroleum refining/petrochemicals, and food industries. Estimates of the demand for boiler fuels showed that, in current manufacturing uses, the maximum potential will be nominal in 1980 but could reach 5×10^{15} Btu per year in 2000. This quantity is equivalent to 2.3 million barrels per day of oil or about 40 percent of the total industrial demand for boiler fuels. Current uses and additional potentials associated with new applications of fluidized-bed combustion and with a higher level of in-plant generation of electricity could reach a combined maximum potential of about 8×10^{15} Btu per year.

Engineering and cost analyses for industrial boiler systems having a steam output of 100,000 pounds per hour indicate that:

- Much of the higher cost of burning coal instead of oil is due to the extensive fuel-handling and waste-handling facilities required for coal.
- Meeting environmental standards with high-sulfur fuels is much more costly than burning low-sulfur fuels; the cost of a flue gas scrubber and waste disposal system exceeds the cost of a boiler.
- Fluidized-bed combustion of high-sulfur coal is economically competitive with conventional combustion of the same coal in conjunction with stack gas scrubbing; future technological improvements could reduce the cost of the fluidized-bed boiler system significantly.
- Fluidized-bed combustion does not appear to be economically competitive with conventional coal combustion in areas where low-sulfur coal is readily available without excessive transportation costs.
- Larger boiler capacities favor fluidized-bed combustion since it may be possible to ship factory-assembled units with steam output of up to 250,000 pounds per hour; conventional coal-fired boilers of this capacity must be assembled in the field at a significant increase in cost.

Activities currently under way include the development of estimates of the most realistic and the minimum potentials for fluidized-bed combustion of coal, evaluation of the effects of fluidized-bed combustion applications, and determination of the specific technical requirements for representative industrial boiler installations. A market survey of companies that have a potential interest in fluidized-bed combustion of coal is also being planned.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

During the quarter, Exxon developed specific technical requirements for representative industrial fluidized-bed boilers. Previous cost estimates were extended to include boilers with larger and smaller capacities than 100,000 pounds per hour. Exxon also reviewed coal consumption statistics, suggested a marketing strategy for the introduction of fluidized-bed combustion technology to potential industrial users, and outlined some advantages of coal-fired fluidized-bed combustion technology. In addition, the market survey of selected industries was planned to learn the attitudes of the industries toward coal firing and fluidized-bed technology.

Economic, Energy, and Environmental Analyses

The engineering and cost analysis covering variations of economic factors such as boiler size increases was completed. Cost estimates were presented for boilers with capacities larger and smaller than 100,000 pounds per hour (the basis for previous cost estimates); steam outputs of these boilers were 50,000, 200,000, and 400,000 pounds per hour. Fluidized-bed combustion technology scaled slightly better than scrubber technology. Based on high investment costs for coal versus oil and the distribution of boiler sizes in the industrial boiler population, a boiler with a steam output of 100,000 pounds per hour is about the smallest boiler size for which a general program to substitute coal for gas and oil will be viable from overall considerations. In general, the potential for coal-fired fluidized-bed combustion technology will be enhanced as the average size of boiler increases, i.e., the technology will be more applicable to industries that require large boilers.

A special project review meeting was held during the quarter to discuss the validity of coal consumption statistics. In preparation for this meeting, Exxon reviewed coal consumption statistics and other evidence from several government and industry sources and concluded that:

- The percentage of coal, relative to other fuels, as an industrial boiler fuel is still decreasing, but a reversal of this long-term trend is in prospect.
- The absolute level of coal consumption in industrial boilers will be higher in 1976 than in 1975, primarily because manufacturing activity is expected to be at a higher level.
- The effect of anticipated petroleum scarcity on coal-firing of industrial boilers has yet to be felt on a net basis.

Several areas of fluidized-bed combustion technology were identified in which real or apparent problems exist. Resolution of these uncertainties is essential before widespread application of coal-fired fluidized-bed combustion can be expected. The principal uncertainties include the availability of suitable limestone, disposal of waste solids, maintenance of desired particle size distribution in the fluidized bed, and retrofitting of fluidized-bed combustion systems to existing industrial boilers. Economically, the outlook for limestone availability and solid waste disposal is favorable. Retrofitting is economically unattractive in most cases. A low cost solution is needed to control buildup of oversized particles in the fluidized bed. (A significant cost is associated with hot solids screening for removal of clinkers and rocks. If such screening proves to be unnecessary, fluidized-bed combustion would improve in outlook relative to alternative coal-use technologies.)

Development of specific technical requirements for representative industrial fluidized-bed boilers was accomplished during the quarter. The list of representative boilers submitted to the sponsors is presented in Table XI-1.

Efforts in several areas had the ultimate objective of establishing and reinforcing the basis upon which a considerable potential is seen for coal-fired fluidized-bed combustion technology as applied to industrial boilers. Fluidized-bed combustion has potential advantages over scrubber technology even though estimates of current costs are similar. Definite advantages of coal-fired fluidized-bed technology outlined by Exxon included reliability of the fuel supply, versatility of the technology, flexibility and respect to coal type, and ability to control nitrogen oxide emissions.

A marketing strategy for the introduction of fluidized-bed combustion industrial boiler technology was suggested. The approach focuses on the item of greatest concern to the prospective industrial customer for this technology, namely, reliability. Risks of initial unfavorable experience may be minimized by following a phased introductory approach. Suggested marketing targets for the first phase of introduction are industrial plants that have been firing coal for years and thus are best equipped to introduce the new technology at the lowest possible risk and cost.

Market Survey

Plans for the market survey were made to learn the attitudes of several dozen industrial corporations toward coal-firing and fluidized-bed combustion technology. The operations of the companies selected cover a wide range of manufacturing activity, but the selection was weighted toward those with a potential interest in fluidized-bed combustion of coal. Multiplant operators that use coal at some of their locations are included. While many industries are covered, the chemicals, rubber, paper, petroleum refining, and food processing industries are emphasized. The selected industries combine two characteristics: continuous large-scale operations and a large requirement for steam in a given plant. Originally, information was to be requested on a written questionnaire. However, access to statistical information gathered previously by the FEA's Office of Fuel Utilization eliminated this approach. Instead, the survey will focus on attitudinal questions that can be discussed by telephone. The survey has been delayed pending permission from the General Accounting Office.

Table XI-1. REPRESENTATIVE INDUSTRIAL FLUIDIZED-BED BOILERS

Steam Rate and Conditions			Combustion Pressure Level	Limestone Use	New or Retrofit	Probable Degree of Application[a]
Rate (pounds per hour)	Pressure (atm)	Temperature				
<100,000 →	→	→	→	→	→	Low
100,000	8.6	353° F (saturated)	Atmospheric	Once through	New	Moderate
100,000-250,000	44.25	700° F	Atmospheric	Once through	New	Fairly high
400,000 or greater	44.25	700° F	Atmospheric	Once through	New	Moderate
←	←	←	All pressurized designs	→	→	Uncertain
←	←	←	←	All regenerative designs	→	Uncertain
←	←	←	←	←	All retrofit applications	Low

[a]In terms of numbers of boilers; applicability is expected to increase with boiler size.

XII. R&D PLANNING ASSISTANCE SERVICES

THE MITRE CORPORATION
McLEAN, VIRGINIA

Contract No. E(49-18)-1779
Total Funding: $1,840,000

INTRODUCTION

R&D planning assistance services are being provided by The MITRE Corporation under the sponsorship of ERDA. Under this contract, initiated in December 1974, MITRE is to provide technical and other assistance in the preparation and implementation of national program plans and analyses for R&D in coal-based advanced power and direct combustion systems. Advanced power systems research is directed toward development of power conversion systems that will permit, in an environmentally acceptable manner, efficient and economically competitive generation of electric power using coal and coal-derived fuels. The advanced power systems being considered in this program include open-cycle gas turbines (especially in combined-cycle configuration), closed-cycle gas turbines, and alkali metal vapor turbines. Direct combustion research, including atmospheric (utility, industrial, retrofit) and pressurized (utility, industrial) systems, seeks to develop commercial systems for efficient burning of coal in an environmentally acceptable manner.

PROGRAM DESCRIPTION

Provision of R&D planning assistance services for advanced power and direct combustion systems requires complete systems engineering and technical direction support. This support comprises five tasks:

Task I—Program Planning
- *Definition and ranking of system selection criteria*
- Trade-off analyses to determine relative merits of the alternative candidates and to place the program plans on a technically and economically defensible base
- Identification and ranking of the substantive technical issues that are key to successful development and implementation
- Support of the program plan by a substantive technical effort, including safety analyses, market penetration studies, cost-benefit analyses, technical risk assessment, scaling studies, test results assessment, etc.
- Updating the program plan to reflect technology advancements, funding level changes, and program decisions, and supporting the plan by development of budget justifications and relevant congressional hearing documents

Task II—Project Planning
- Development of basic R&D action documents
- Support of the project plans by appropriate technical and economic analyses

Task III—Project Implementation Support
- Assistance in management plan formulation
- Assistance in development of technical specifications
- Assistance in the coordination and integration of projects

Task IV—Program Review Support

Task V—Systems Engineering and Evaluation

Technology assessment, review, and documentation efforts are underway. The subcontractors assisting MITRE in this effort are Battelle Columbus Laboratories, Wittreich Associates, and Strasser Associates.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

R&D planning assistance services provided to ERDA during the fourth quarter of 1975 included work on projects related to both advanced power systems and direct combustion systems. Activities pertaining to advanced power systems included assistance with the preparation of a national program plan, review of "A National Plan for Energy RD&D: Creating Energy Choices for the Future," survey of open-cycle gas turbine development, and evaluation of ceramic component technology. Among the activities supporting direct combustion systems projects were the updating of Volume II of the national fluidized-bed combustion program plan, assistance to the Morgantown Energy Research Center (MERC) in developing design criteria for a Component Test and Integration Facility (CTIF), and provision of technical and engineering inputs related to the multicell fluidized-bed boiler being developed by Pope, Evans and Robbins, Inc. (PER).

Advanced Power Systems

Work continued on the preparation of the national advanced power systems program plan document. The milestone and flow charts describing MITRE's view of the baseline program plan were completed. In addition, MITRE reviewed an ERDA report, "A National Plan for Energy RD&D: Creating Energy Choices for the Future," as it pertained to the advanced power systems program and suggested changes and supplied additional material for a revised report. MITRE also surveyed research and development activity related to open-cycle gas turbine development and visited Wright Patterson Air Force Base, General Electric, Westinghouse, and United Technologies to assess ceramic component technology. The results of this effort suggest the need for a government team to provide an unbiased assessment of the worldwide state-of-the-art in this field before initiating a competitive procurement for ceramics technology development.

Systems engineering and evaluation activities included:

- A visit to General Electric's industrial turbine development and manufacturing facility in conjunction with the study of the state-of-the-art of ceramic component technology.
- Completion of the analysis and map illustration of coal-based electric power generation.
- Analysis of power generation equipment warranty performance guarantee information from several equipment manufacturers.
- Preparation of a position paper on the FT-50, the 100 Mw gas turbine designed by United Technologies for utility base-load application.
- Preparation of a working paper analyzing the potential water use implications and benefits of advanced power systems.
- Analysis of the effect of the hydrogen-to-carbon ratio on the formation of nitrogen oxides. MITRE determined that formation of nitrogen oxides is dependent on the flame temperature and the amount of nitrogen in the fuel, and that the hydrogen-to-carbon ratio affects only the flame temperature.
- Continuation of planning for a workshop on the commercialization of advanced power systems.
- A visit to Oak Ridge National Laboratory to discuss work on liquid metal systems for utility application.
- Completion of a cost-benefit analysis of advanced power and fluidized-bed combustion systems, including development of a data base of existing and planned generating units in the United States.

Battelle continued reviewing the current advanced power systems technology and analyzing performance, cost, technical risks, reliability, and environmental and safety factors. Battelle also continued its evaluation of the cost and performance aspects of the parametric analyses conducted as part of the Energy Conversion Alternatives Study. Wittreich Associates completed the survey and analysis of the potential utility market for advanced power systems and fluidized-bed combustion systems and prepared a report, "Commercialization Opportunities for New Coal Technologies," that was reviewed by MITRE and presented to ERDA. Strasser Associates supplied recommendations to MITRE regarding the general approach to be taken in cost-benefit analyses, reviewed preliminary plans for the advanced power systems workshop, and assisted MITRE in defining the content of the national advanced power systems program plan document.

Direct Combustion Systems

During the quarter, Volume II, program plan of the national fluidized-bed combustion program was updated. The draft version was being reviewed and edited for publication.

MITRE provided technical assistance to MERC in support of (1) the CTIF to be used for studying atmospheric fluidized-bed combustion systems and (2) the multicell fluidized-bed boiler being developed by PER. Assistance included development of functional design criteria, review of a draft description of CTIF, provision of technical and engineering inputs to support contract modifications related to the PER project, and assistance with the development of a procurement analysis system to ensure that milestone/decision plans are followed.

In other support of ERDA's direct combustion program, MITRE personnel submitted documents on potential short-term energy programs, including coal-oil slurry firing to displace part of the oil used in totally oil-fired combustion systems. In addition, MITRE participated in a review meeting in London on the pressurized pilot plant to be built in the United Kingdom under the auspices of IEA.

Systems engineering and evaluation activities included:

- Analysis of the calcium requirements expected in the PER 30 Mw pilot plant.
- Preparation of a preliminary environmental assessment of a site at MERC for the atmospheric pressure CTIF.
- Arrangement and handling of the Fourth International Conference on Fluidized-Bed Combustion.
- Initiation of planning for a workshop on the commercialization of fluidized-bed combustion systems.

XIII. TECHNICAL AND ENGINEERING SERVICES

GILBERT ASSOCIATES, INC.
READING, PENNSYLVANIA

Contract No. E(49-18)-1236
Total Funding: $2,095,000

INTRODUCTION

Under contract with ERDA, Gilbert Associates, Inc., is providing technical and engineering services in support of a program to find clean and efficient methods for utilizing coal to produce electric power. Some of these services are in direct support of programs involving fluidized-bed combustion of coal with in situ sulfur removal using limestone. (Gilbert Associates also provides services in support of programs involving combined-cycle systems using low-Btu fuel gas and magnetohydrodynamics.) ERDA's electric power program will culminate in the operation of demonstration plants that utilize advanced power systems for the clean generation of electricity from coal.

PROGRAM DESCRIPTION

Initiated in November 1972, this program is oriented to surveying the progress of novel and advanced power systems technology and providing ERDA with additional technical expertise to evaluate the feasibility and economics of the various electric power systems. Much of the effort involves:

- Identifying proven methods and components that could be used in pilot plants wherever practical.
- Identifying major equipment under development that should be designed for flexibility of operation to permit the investigation of variations in process conditions.
- Recommending to ERDA independent subcontracts that should be initiated to develop components and subsystems that may significantly improve the performance and economics of electric power plants.

Gilbert Associates representatives provide technical assistance in monitoring work performed on power systems contracts by reviewing progress reports and evaluating proposals for expansion or modification of development work as required to expedite progress and optimize results. Gilbert Associates also helps coordinate appropriate technical information among contractors involved in similar technical disciplines and helps perform technical and economic studies as directed by ERDA. Recommendations are presented to ERDA for action.

PROGRESS DURING OCTOBER-DECEMBER 1975

Summary

Activities in support of ERDA's combustion program included continuing design review and construction management assistance with the multicell fluidized-bed boiler project being developed by Pope, Evans and Robbins (PER) and preparation of a draft report on an engineering economy study of the modular integrated utility system (MIUS). Gilbert also assisted ERDA in work on a proposed Component Test and Integration Facility (CTIF) for studying atmospheric fluidized-bed combustion systems. Work on cleanup systems for use with fluidized-bed combustion systems included studies of methods of sampling and measuring particulates in combustion systems, support of ERDA's effort to evaluate and select stable and regenerable sorbents for sulfur removal, and review of developments in high-temperature, high-pressure particulate removal systems.

Fluidized-Bed Combustion

Gilbert continued to provide assistance to ERDA on the PER multicell fluidized-bed boiler. This assistance included design review, construction management consultation on site, proposal review, test plan development, and meeting participation. A final draft of the support document for the second Request for Contract Action pertaining to the Rivesville site was transmitted to ERDA. This document included work statements, budget breakdowns, schedules, and justification for the additional efforts. Information on the status of the instrument and control equipment for this project was reviewed with PER and Champion. As requested by ERDA, a study was completed of alternate methods of getting coal of high and low sulfur content from the truck dump hopper to the distribution hopper for this facility. ERDA also requested that Gilbert prepare computerized tracking documents, drawing lists, and equipment lists for the PER Rivesville project. The information required for this effort is being collected. In addition, the Rivesville multicell fluidized-bed design is being studied to determine the degree of correlation between it and the Alexandria, Virginia, fluidized-bed module. The sulfur dioxide and nitrogen oxide removal capacity of Alexandria's process development unit was reviewed. This review included the determination of the parameters involved, analysis of the available data, and study of the use of sorbents.

A draft of the report, "An Engineering Economy Study of a Commercial Coal Fueled MIUS Concept," was completed and submitted to ERDA for review.

Gilbert provided layout and detail design assistance for the proposed Morgantown Energy Research Center (MERC) CTIF to be used for studying atmospheric fluidized-bed combustion systems. Gilbert also assisted The MITRE Corporation in developing the experimental program for the CTIF and reviewed the draft of the CTIF fluidized-bed combustion test plan to be submitted by MERC. This program includes experimental work needed to increase fundamental knowledge of fluidized-bed combustion, provide inputs for analytical modeling, and provide scale-up information.

The corrosive effects of sodium chloride are being studied to provide a basis for determining the deleterious effects of sodium chloride on various materials used in the combustor and auxiliary systems.

A comparison of research results from PER, the British Coal Utilization Research Association, and the National Coal Board (United Kingdom) has been initiated as part of the preparation of test plans for ERDA facilities.

Cleanup Systems

Studies of methods of sampling and measuring particulates in combustion systems included a visit to Spectron Development Laboratories to discuss their laser light scattering instrument. Gilbert personnel also reviewed the principles behind a light scattering instrument proposed by Leeds and Northrup.

In support of ERDA's work to evaluate and select stable and regenerable sorbents for sulfur removal in coal combustion processes, Gilbert partially evaluated the applicability of alternate regenerable sorbent for removing sulfur compounds in fluidized-bed coal combustion systems, based on theoretical and laboratory studies conducted by Radian Corporation under the sponsorship of EPA. In addition, new sorbent materials for testing in ERDA-supported pressurized and atmospheric fluidized-bed units were evaluated from a literature survey and discussions with sorbent/catalyst manufacturers. The properties of metal oxide sorbents were reviewed in detail for application to fluidized-bed combustion.

Developments in high-temperature, high-pressure particulate removal systems for pressurized and atmospheric fluidized-bed combustion systems were reviewed during the quarter. Emphasis was placed on studies of filters, cyclones, and electrostatic precipitators. Also, Gilbert personnel reviewed the status of the development of granular-bed filters, based on a literature survey and discussions with developers, and conducted a preliminary evaluation of the granular-bed filter being used by Combustion Power Company, Inc., to determine the reason for the failure of the filter support tube. The construction material used was determined to be one of the probable causes of failure.

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GLOSSARY

The intent of this glossary is to give a general definition of terminology as used in this report. A glossary is considered desirable because of the diverse origin of the technology and broad spectrum of potential readers. For more precise and detailed definitions, the reader is referred to *The Annual Book of ASTM Standards* published by the American Society for Testing Materials (ASTM), *Chemical Engineers' Handbook* by R. H. Perry and C. H. Chilton, and *A Dictionary of Mining, Mineral, and Related Terms* published in 1968 by the U.S. Department of the Interior.

Å – Angstrom unit, a unit of length equal to 10^{-10} meters or 10^{-4} microns, generally used as the unit for describing interatomic distances; as an example, the carbon atoms in diamond are 1.5 Å apart.

absorption – the dissolution of a gas in a liquid.

adiabatic – any process where heat is neither given off nor absorbed.

adsorption – the physical and chemical adherence of a gas to the surface of a solid.

anthracite coal – any coal containing 86 to 98 percent fixed carbon, on a dry, mineral-matter-free basis.

aromatic hydrocarbon – an unsaturated cyclic hydrocarbon containing one or more six-carbon rings.

ash – theoretically, the inorganic salts contained in coal; practically, the residue from the combustion of dried coal that has been burned at 1,380° F.

bituminous coal – a broad class of coals containing 46 to 86 percent fixed carbon and 20 to 40 percent volatile matter.

blow down – the removal of liquids from a process vessel by the application of pressure.

bottoming cycle – the lower temperature thermodynamic power cycle of a combined-cycle system.

Btu – British thermal unit, the quantity of energy required to raise the temperature of one pound of water one degree Fahrenheit.

caking – the softening and agglomeration of coal as a result of the application of heat.

calcine – to heat a solid to a high temperature to cause the decomposition of hydrates and carbonates.

char – the solid residue from coal after the removal of moisture and volatile matter, i.e., essentially ash plus fixed carbon.

closed cycle – a thermodynamic power cycle in which the working fluid is recycled.

al – a natural solid material consisting of amorphous elemental carbon with various amounts of organic and inorganic compounds.

coke – a solid consisting primarily of amorphous carbon having certain properties of strength, cell structure, and minimum impurities, and manufactured by the thermal decomposition of petroleum residues and certain types of coal.

coke breeze – coke particles smaller than 1/2 inch in size.

combined cycle – two sequential thermodynamic power conversion systems operating at different temperatures.

coupon – a polished metal strip used to measure the rate of corrosion of the metal in a specific gaseous or liquid environment.

cracking – the partial decomposition of high-molecular-weight organic compounds into lower-molecular-weight compounds, generally as a result of high temperatures.

cyclone separator – essentially a settling chamber to separate solid particles from a gas, in which gravitational acceleration is replaced by centrifugal acceleration.

dolomite – a mineral having the chemical formula $CaMg(CO_3)_2$, i.e., a carbonate of calcium and magnesium.

Dowtherm – trademark for a series of eutectic mixtures of diphenyl oxide and diphenyl used as high-temperature heat-transfer fluids.

economizer – a heat exchanger for recovering heat from flue gases and using it to heat feedwater or combustion air.

elutriation – the preferential removal of the small constituents of a mixture of solid particles by a stream of high-velocity gas.

endothermic – a process in which heat is absorbed.

enthalpy – a form of thermal energy defined as the sum of the internal energy of a system plus the product of the system's volume and pressure.

eutectic – that combination of two or more components which produces the lowest melting temperature.

exothermic – a process in which heat is liberated.

fixed bed – solid particles in intimate contact with fluid passing through them, but too slowly to cause fluidization.

fixed carbon – theoretically, the carbon content of coal which exists in the elemental state; practically, the difference between 100 percent and the sum of ash, moisture, and volatile matter percentages.

fluidization (dense phase) – the turbulent motion of solid particles in a fluid stream; the particles are close enough as to interact and give the appearance of a boiling liquid.

fluidization (entrained) – solid particles transported by a high-velocity fluid stream with little or no solid interaction.

freeboard – the space in a fluidized-bed reaction between the top of the bed and the top of the reactor.

free swelling index – a standard test that indicates the caking characteristics of coal when burned as a fuel.

gasification of coal – the conversion of solid coal into a gaseous form by any of a variety of chemical processes.

high-Btu gas – a gas, largely methane, having a heating value of 900 to 1,000 Btu per cubic foot, which approaches the value for natural gas.

high heating value (HHV) – the heat liberated during a combustion process in which the product water vapor is condensed to a liquid.

hydrocracking – the combination of cracking and hydrogenation of organic compounds.

hydrotreating – a process involving the reaction of hydrogen with hydrocarbon mixtures for the removal of such impurities as oxygen, nitrogen, and sulfur.

ideal gas – any gas whose equation of state is expressed by the ideal gas law, namely $PV=RT$ where P is the pressure, V is the volume of one mole, R is the gas constant, and T is the absolute temperature.

ignition temperature – the minimum temperature necessary to initiate self-sustained combustion of a substance.

lignite – a low rank of coal between peat and subbituminous.

limestone – a sedimentary rock composed mostly of calcium carbonate ($CaCO_3$) and possibly some magnesium carbonate ($MgCO_3$).

liquefied petroleum gas (LPG) – those hydrocarbons that have a vapor pressure (at 70° F) slightly above atmospheric (such as propane and butane); kept in liquid form under a pressure higher than 1 atm.

lock hopper – a mechanical device that permits the introduction of a solid into an environment of different pressure.

low-Btu gas – a gas having a heating value of 150 to 350 Btu per cubic foot; when made from coal, water, and air, it contains varying quantities of carbon monoxide, carbon dioxide, nitrogen, hydrogen, and methane.

methanation – the production of methane (CH_4) from a mixture of carbon monoxide and hydrogen.

micron – a unit of length equal to one millionth of a meter.

noncoking – a coal that does not form coke under normal coking conditions.

olefinic hydrocarbon – a class of unsaturated hydrocarbons containing one or more double bonds and having the general chemical formula C_nH_{2n}.

open cycle – a thermodynamic power cycle in which the working fluid passes through the system only once and is then exhausted to the atmosphere.

perfect gas – see ideal gas.

pilot plant – a chemical process plant containing all the processes of a commercial unit, but on a smaller scale, for the purpose of studying the process.

prilling tower – a tower that produces small solid agglomerates by spraying a liquid solution in the top and blowing air up from the bottom.

process development unit – a laboratory-sized system used to study the effects of process variables on performance.

proximate analysis – analysis of coal based on the percentages of moisture, volatile matter, fixed carbon, and ash.

pyrolysis – thermal decomposition of organic compounds in the absence of oxygen.

refractory – a material capable of withstanding extremely high temperatures and having relatively low thermal conductivities.

saturated hydrocarbon – a hydrocarbon in which all bonds are single covalent bonds and none are double or triple bonds.

sensible heat – that heat which results in only the elevation of the temperature of a substance with no phase changes.

sintering – the agglomeration of solids at temperatures below their melting point, usually as a consequence of heat and pressure.

slag – a molten mixture of various metallic oxides and salts.

slurry – a suspension of pulverized solid in a liquid.

space velocity – the volume of a fluid (usually measured at standard conditions) passing through a unit volume in a unit time; units are in reciprocal time.

standard cubic foot (SCF) – the volume of a gas standard conditions of temperature and pressure. The

American Gas Association uses moisture-free gas at 60° F and 30 inches of mercury (1.0037 atm) as its standard conditions. The pressure standard is not universal in the gas industry; 14.7 psia (1.000 atm) and 14.4 psia (0.980 atm) are also used. The scientific community uses 32° F and 1 atm as standard conditions.

stoichiometry – the definite proportions in which molecules react chemically to form new molecules.

stripping – the removal of the more volatile components from a liquid mixture of compounds.

subbituminous coal – the rank of coal between bituminous and lignite, classified by ASTM as having a range of heating values between 8,300 and 11,000 Btu per pound on a moist mineral-matter-free basis.

superficial velocity – the linear velocity of a fluid flowing through a bed of solid particles calculated as though the particles were not present.

superheater – a heat exchanger which adds heat to the saturated steam leaving a boiler.

synthesis gas – a mixture of hydrogen and carbon monoxide which can be reacted to synthesize a hydrocarbon.

tar (coal) – a dark brown or black, viscous, combustible liquid formed by the destructive distillation of coal.

topping cycle – the higher temperature thermodynamic power cycle of a combined-cycle system.

turned down – the reduction of reactor flow rates to a fluidized-bed reaction vessel.

ultimate analysis – the analysis of coal based on the percentages of chemical elements.

volatile matter – those constituents of coal, exclusive of moisture, that are liberated from a sample when heated to 1,750° F (for 7 minutes) in the absence of oxygen.

water gas shift – the reaction between water vapor and carbon monoxide to produce hydrogen and carbon dioxide or the reverse: $CO + H_2O \rightleftarrows H_2 + CO_2$.